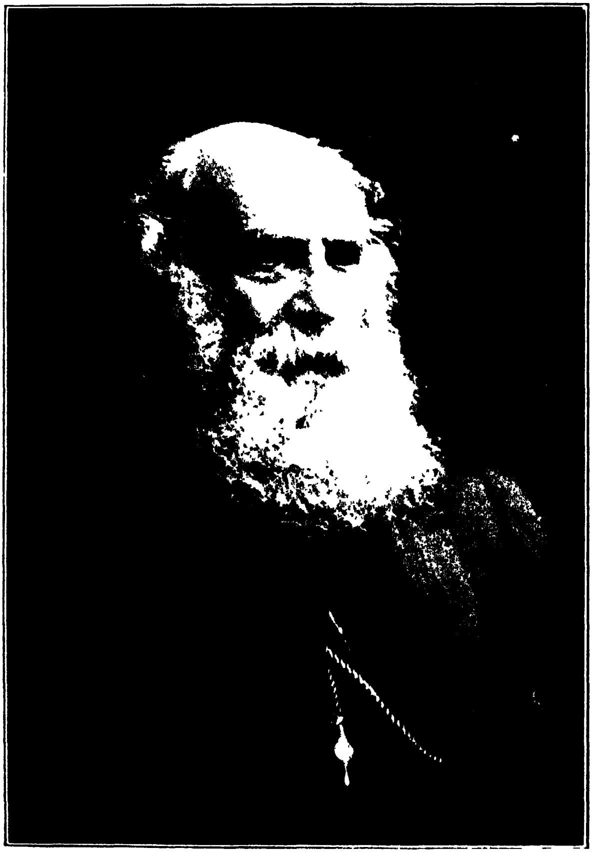
THE ELECTRON THEORY



DR. G. JOHNSTONE STONEY

From a photograph by Elliott & Fry

THE
ELECTRON THEORY

A POPULAR INTRODUCTION TO THE NEW THEORY OF ELECTRICITY AND MAGNETISM

BY

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COMPILER OF "CONTEMPORARY ELECTRICAL SCIENCE"

WITH A PREFACE

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PREFACE

In 1811—nearly a hundred years ago—Avogadro promulgated the important law which bears his name, and which gives expression to the fact that all the more perfect gases, when reduced to the same pressure and temperature, will contain within a given volume the same number of gaseous molecules. The fact was established: but the reason why it is so was not then understood, nor till long afterwards, when in the forties and fifties of the last century some of the activities that go on within gases became gradually known. Until these later dates it was erroneously supposed, even by careful students of nature, that natural objects which to our senses appear at rest—such as stones, coins, books, air which has been left for a long time undisturbed within a room—are in reality devoid of any internal motion. As to gases, one of the illustrations made use of in those days to help students to picture what they were supposed to be like, was that the molecules of a gas may perhaps resemble the stationary bubbles of a froth, which by expanding when warmed, contracting when cooled, and by pressing against one another and against the walls of a containing vessel, behave

in these respects very much like a gas. Under this view, Avogadro's Law was expressed by saying that the bubbles, or quasi-bubbles, are all of the same size whatever the gas may be, provided that they are compared with one another when at the same temperature and pressure.

It was about sixty years ago when there appeared the first glimmerings of the knowledge which has since ripened into that which we now possess, that neither the molecules of any natural object nor the parts of which those molecules consist are ever at rest; that, on the contrary, swift and orderly movements are ever in progress among them and within them; and that where bodies appear to us to be stationary, it is only because this great internal activity is on too small a scale, the parts moving too tiny, and the motions subject to too rapid changes of direction for senses like ours even when assisted by the microscope to obtain any suggestion that all this activity is going forwards. Accordingly, until other means than direct observation of arriving at the truth were discovered, every one remained under the delusion that the objects about us on the earth could be "brought to rest"—*i.e.* absolutely freed from every motion except the celestial motion, which is consequent upon their being on a planet which rotates upon an axis, revolves in an orbit round the sun, and accompanies the solar system in its peregrinations through space.

There was one man—an Englishman—who above

sixty years ago perceived that this view of nature was a mistake, at least with reference to matter in the gaseous state. J. J. Waterston, in 1845 submitted a memoir to the Royal Society, in which he showed that the recognised properties of the more perfect gases indicate with emphasis that instead of consisting of stationary molecules pressing against one another, they are in reality swarms of much smaller bodies, so small that they leave much of the space unoccupied, in which they dart about amongst one another with extraordinary activity, and produce gaseous pressure by encountering one another or where turned back by the walls of a containing vessel. Waterston's contention led to results at variance with the views entertained by scientific men at the time, and his great discovery with the arguments in favour of it, were withheld from publication until long afterwards; so that this great advance in knowledge did not become generally known until, shortly afterwards, Professor Clausius of Geneva rediscovered the kinetic constitution of gases. His announcement of it was received with much scepticism. However, Clausius persisted, and in a masterly series of papers published in the later forties and in the fifties of the nineteenth century he met objections, and piled proof upon proof, until the evidence could no longer be resisted. In the later developments of the theory he was assisted by other scientific men, among whom J. Clerk Maxwell was pre-eminent.

Until some information can be acquired respecting the magnitudes with which we are dealing when investigating any branch of nature's operations, we continue to be unable to form a satisfactorily clear notion of those operations. In the domain of Molecular Physics the first magnitude that was ascertained was when Clausius succeeded in estimating the speeds with which molecules of a gas are travelling about. At any one instant the individual molecules are darting about with very different speeds, but at each temperature there is a certain mean speed towards which the encounters which prevail within a gas tend to bring any speeds which too much differ from it, and round which the innumerable speeds tend to group themselves. The mean speed so defined is not the arithmetic mean of the values of v, but the square-root of the arithmetic mean of the values of v^2. This mean speed Clausius succeeded in finding to be about

$$485\sqrt{\frac{\tau}{273\cdot\rho}} \text{ metres per second} \quad . \quad . \quad . \quad 1\ (a)$$

Where τ is the absolute temperature of the gas estimated in centigrade degrees, and ρ the relative specific gravity of the gas compared with air. Expressed in miles per hour this mean speed is

$$1085\sqrt{\frac{\tau}{273\cdot\rho}} \text{ miles per hour} \quad . \quad . \quad . \quad 1\ (b)$$

The arithmetic mean of the various speeds that

prevail among the molecules is a different mean from that given above. It is somewhat less, and to obtain it we multiply the above value by 0·92132. Thus the arithmetic mean is

$$447\sqrt{\frac{\tau}{273 \cdot \rho}} \text{ metres per second.}$$

Again, the temperature of our laboratories when experiments are being made in them may be taken to be about 16° C., which is the same as $\tau = 289$. Introducing this value for τ, we find that the *arithmetic* mean of the speeds at this temperature is

$$460\sqrt{\frac{1}{\rho}} \text{ metres per second} \quad . \quad . \quad . \quad 2\,(a)$$

which is the same as

$$1022\sqrt{\frac{1}{\rho}} \text{ miles per hour} \quad . \quad . \quad . \quad . \quad 2\,(b)$$

so that, in the air about us, and at the temperatures to which we are most accustomed, the molecules of its principal gases are travelling with speeds of which the arithmetic mean is more than 1000 miles per hour. In order to get the arithmetic mean for each gaseous constituent of our atmosphere we must insert in the last expression the value of ρ for each gas. We thus find what it is in nitrogen, oxygen, argon, aqueous vapour, and the rest.

The next important molecular magnitude to be

discovered was when Professor Maxwell in 1859 and 1860 deduced from observations on the viscosity of gases, and also from the rate of diffusion of olefiant gas into air, the mean length of the little straight path along which a molecule of air darts between consecutive encounters. It is, at the temperature of 15° C. and at the pressure of an atmosphere, about

7·6 eighthet-metres . . . 3

which is the mean of three determinations made by Maxwell. By an eighthet is to be understood the fraction represented by a unit in the eighth place of decimals, or by the symbol 10^{-8}; and eighthet-metre is a convenient abbreviation for eighthet of a metre in like manner as a quarter-inch means the quarter of an inch.

It is worth taking notice, here, that the mean length of the free paths of the molecules between their encounters, although a giant among molecular magnitudes, falls short of the smallest interval which the microscope can detect. Two minute specks on the stage of a microscope, even if separated by twice this interval, would nevertheless be blurred together into the appearance of a single object, when viewed under the most favourable conditions, through the best of microscopes handled with the utmost skill.

By comparing this small measure with the average total distance which the molecule travels in a second, which we have found to be 460 metres

(see equ. 2 (a)), we learn that the path pursued by the molecule within one second is a zigzag course, divided on the average into 6,000,000,000 little straight free paths between the encounters that it meets with.

When Maxwell had determined the average length of the free path, it was easy to form a preliminary estimate of the number of molecules that are present; and, accordingly, this was attempted by the present writer in 1860, immediately after the publication of Maxwell's papers. What was sought in this preliminary effort was to determine which power of 1000 is nearest in the geometric series to the number of molecules in a cubic millimetre of gas. This was found to be the sixth power, which is 10^{18}; from which it followed that the actual number of molecules is to be looked for within the group of numbers that intervenes between $10^{18} \div \sqrt{1000}$ and $10^{18} \times \sqrt{1000}$, *i.e.* it is a number greater than $3{\cdot}16 \times 10^{16}$ and less than $3{\cdot}16 \times 10^{19}$. Other determinations of this important physical constant have since been made, and some from data admitting of much closer approximation. From these we learn that we may now accept 4×10^{16} as a trustworthy and reasonably close approximation to the number of gaseous molecules within a volume which is not far from being one cubic millimetre—the gas, or mixture of gases, being at or near standard temperature and pressure. To this number of molecules within each cubic millimetre of dry air the principal constituents of

the earth's atmosphere contribute nearly in the following proportions:[1]—

Nitrogen	4 × 7810 000000 000000	molecules of	N_2
Oxygen	4 × 2090 000000 000000	„	O_2
Argon	4 × 100 000000 000000	„	A
Carbon dioxide .	4 × 4 000000 000000	„	CO_2
Neon (about) . .	4 × 100000 000000	„	Ne
Helium (perhaps) .	4 × { 10000 000000 or 5000 000000 }	„	He

Minor constituents are also present, but in smaller numbers. These are krypton, xenon, and hydrogen, with probably a few molecules of ammonia and some of the oxides of nitrogen; and of course there will be a variable amount of aqueous vapour present, if the air has not been completely dried.

These various determinations enable us to construct our first picture of what each cubic millimetre of the air about us really is. We are to imagine these enormous swarms of little missiles dashing about in every conceivable direction, each of the missiles successively encountering and occasionally grappling with about six thousand millions of its neighbours every second, and darting along the free paths between these encounters

[1] A vacuum formed by pumping air out of a receiver till the residual pressure is reduced to the 10,000,000th of an atmosphere, would usually be spoken of as an exceedingly high vacuum. Nevertheless, it follows from what has been mentioned in the text, that, throughout this so-called vacuum, there remain about 4,000,000,000 molecules *in every cubic millimetre* of the space within the receiver. To get the numbers of molecules of the various gases, within each cubic millimetre, strike off the last seven ciphers from each of the numbers of the table in the text.

with various speeds, but speeds that are so high that they average more than a speed of 1000 miles per hour. Wonderful as this picture is, we shall presently find that it falls almost infinitely short of the far more astonishing reality. We are enabled to see that this is so, by being already in a position to advance one step nearer to the reality, and by the prospect that then opens before us of further extensions into the still more deeply seated operations which are being carried on by nature. In fact—

While the investigations which revealed to us the kinetic constitution of gases were in progress in the last century, another line of inquiry was being simultaneously pushed forward which touched upon deeper mysteries of nature. As an introduction into this new region of exploration it will be convenient to recall one of the facts already referred to, that while the free paths of the molecules have very various periods, their average duration is about the six thousand millionth of a second. Let us then compare this brief duration with the vastly smaller periodic times of the alternating event which we call light. When this is done it is found that while a molecule of air has been travelling between one encounter and the next, 60,000 double vibrations of red light have on the average taken place, and twice that number of the extreme violet ray; and as the periods of all the motions within a molecule which give rise to visible spectral rays must lie between these limits,

we are forced to admit that either that immense number of orbital motions have been on the average executed by electrons within the molecule during each of its flights, or else that periodic motion of some one or more of the electrons has been going on of so complex a kind that when fully resolved it furnishes that immense number of individual revolutions. It is now no longer surprising that the temporary perturbation caused while two molecules have been grappling with one another has in most instances abundant time to pass away early in the interval between two encounters, so as to leave the greater part of the motions within the molecule to be executed in the undisturbed manner which the definiteness of the lines of a gaseous spectrum attests to us.

In what way the lines of the spectrum of a gas are brought into existence, may be more definitely understood by remembering that—as can be proved[1]—the motion of each individual electron within a gaseous molecule, however complex that motion may be, is in all cases susceptible of being resolved into "elliptic partials," each of which produces the same physical effects as would an electron revolving pendulously, and therefore with unvarying periodic time, in the corresponding ellipse. Now, an electron

[1] See the paper on "The Cause of Double Lines, &c. &c.," in the *Scientific Transactions of the Royal Dublin Society*, vol. iv., series ii. p. 563 (1891). In the analysis of motion which is not restricted to one plane, elliptic partials are what correspond to the harmonics that present themselves when motion in one plane is resolved by Fourier's Theorem.

when undergoing periodic motion of any kind, propagates electro-magnetic, that is to say luminous, waves through the surrounding æther; and when the motion is of the simplest kind, viz. pendulous elliptic motion, what it will transmit through the æther is a single undulation which will have the same periodic time as the elliptic motion. A luminous undulation of this kind produces a single line in the spectrum of the gas. Accordingly, each partial whose periodic time is such that the revolutions in its ellipse are repeated some number of times between 60,000 and 120,000, in the 6,000,000,000th of one second of time, will furnish a line in the *visible* part of the spectrum, and its existence is made known to us when we see the line in the spectrum. Partials which have other periodic times produce lines either in the infra-red or in the ultra-violet parts of the spectrum, and though lines so situated are not seen by the eye, their presence can be detected by photography, by observations with the bolometer, and in other ways.

If any of the electricity within a gaseous molecule remains in bulk and is not divided into separated electrons, and if it be capable of moving within a confined space, it will be set surging by the more definite movements of the separate electrons in its neighbourhood. This would give rise to subsidiary effects in the spectrum of the gas, in the neighbourhood of the definite lines produced by the separate electrons. Such subsidiary events have in many instances been observed.

The chemical elements are some of them gases in the state in which they usually present themselves to us. A few of the others can be vapourised in a Bunsen's burner; and the rest can either be vapourised and rendered incandescent in the arc-light, or can be brought into a condition, when an electric spark passes between electrodes of the element, such that molecules will detach themselves and travel along free paths as in a gas. In all these cases each element furnishes its characteristic spectrum of defined lines, each of which is due to a ray of light with its own definite period of undulation. These spectra make manifest the marvellous regularity of the motions that go on within the molecules of each element, when its molecules are freed from being interfered with by neighbouring molecules; and at the same time the complexity of that motion; with other information of the most instructive kind as regards the relations in which the elements stand to one another. But the greatest achievement of all, and one to which we may reasonably look forward, has not yet been effected. No one has yet succeeded in tracing back from the periodicities, the intensities, and the other properties of the lines of the spectrum of an element, what that motion of the electrons within the molecules must have been to have been able to produce these precise effects. The information is given to us by nature in the spectrum exhibited to us. It is written there; but in a language which has not yet been deciphered.

Let us hope that this great discovery, which has thrown its shadow so plainly before us, will have been made before long. The ground has been prepared by many notable investigations—Rydberg's, and Kayser and Runge's, on the series of lines which exist in the spectra of the elements, and the relationships which these investigations have brought to light; the study of the Zeeman effect, which we may hope will within a moderate time be made much more complete than it now is; and the many facts with reference to corpuscles, each of which either is or contains one electron, that have been elicited with great skill by Professor J. J. Thomson—all these and some others are, as it were, so many letters of the writing which has to be deciphered. Preliminary approaches to the actual deciphering have been attempted by the writer. Along with the above we have the dynamical data that the spectrum as we see it, is caused by motions given to the electrons, or more probably to some few among them, by the general shaking up of a molecule when it has left off grappling with another molecule, and when its motions have settled down into that natural permanent state which is consequent upon whatever is the natural periodic swing within the molecule—as modified by the fact that energy is escaping from the molecule through its electrons into the surrounding æther.

If the gas is condensed into a liquid or becomes a solid, the free space about its molecules disappears, or at least so much shrinks, that the perturbations

caused by an encounter have not time to have passed away during any part of the transit of a molecule between one encounter and the next. Accordingly the spectrum of this object is no longer due to the natural swing of the motions within molecules freed from outside interference. While a gas is being condensed the motions within a molecule which have been perturbed during an encounter continue to be confused motions during an increasing proportion of the shortened flight of the molecule. Accordingly the lines of its spectrum become less sharply defined: as the condensation of the gas progresses its spectral lines widen, and ultimately they run together and present the appearance which is called a continuous spectrum, which sometimes occupies part, in other cases occupies the whole extent of the spectrum. Of this kind are the spectra of most solid and liquid elements when rendered incandescent by heat, as well as in that still more familiar case when the electrons that lie near the surface of a body have been set in motion by incident light falling upon them. In all cases we may take it that objects become visible when the negative electrons and the mass of positive electricity within each chemical atom have been displaced in regard to one another, and set swinging in the way that can excite luminous undulations in the surrounding æther.

(1) In olden times the best conception that men could form of a gas was that it was somewhat like a froth of bubbles in which the molecules

of the gas are represented by the bubbles of the froth. In those days even scientific men were not aware that any activities whatever were going on within calm air. (2) Afterwards, when the kinetic constitution of gas became understood, the earlier crude conception was exchanged for a better one in which the molecules were represented as missiles travelling about with marvellous energy, whose numbers it was possible to estimate, as well as the average speed with which they dash about, and the average length of their little journeys. (3) Another conception of nature, both truer and more recondite, was attained when it became understood that the molecules are far more than merely missiles, that while they are travelling about subtile events are all the time going on within each of them, involving rapidly alternating displacements of the electricity with which they are charged, and as a consequence the transmission of alternating electro-magnetic stresses in the form of waves through the surrounding æther. We thus are introduced to smaller entities than the missiles, to the negative electrons of which the number in each chemical atom seems, from a remarkable investigation by Professor J. J. Thomson, to be about the same as the number of times by which its atomic weight exceeds that of hydrogen; with corresponding positive charges in each atom, equal in amount to the sum of its negative electrons, but not like the negative electricity split up into separate electrons. Here, then, the

electron is introduced to us as a new entity. (4) Is not it, too, a complex system within which internal events are ever taking place? And when this question can be answered shall we not be in the presence of the inter-active *parts* of an electron? (5) And do not the same questions arise with respect to these? for there is no appearance of there being any limit to the minuteness of the scale upon which nature works. (6, &c.) Nothing in nature seems to be too small to have parts incessantly active among themselves.

Our present position is one which has been reached by slow steps, and we may reasonably hope that our successors will be able to continue to advance, as there is no visible limit. The inquirer who is now entering upon this department of the study of nature will find it much to his advantage to take as his starting-point the picture of nature, which has taken form in the mind of a thoughtful student of the present state of our knowledge, such as is presented in the following pages. This, however, he should entertain, not like a stereotype plate which must remain as it is, but rather like well and firmly set movable type, susceptible with ease of any improvements the future may bring with it, while before and after each correction it is so firmly fixed in its frame that the most effectual use can be made of it.

G. JOHNSTONE STONEY.

September 1907.

AUTHOR'S PREFACE

TO THE SECOND EDITION

THE very flattering reception accorded to the first edition of this work has encouraged me to spare no pains to bring it up to date. Recent researches have, fortunately, shown it to be unnecessary to make any very sweeping alterations in the text, as their results are in satisfactory agreement with the theory originally set forth in it. Nothing has occurred since last year to shake the faith of physicists in the electron theory, and the work of its detailed application is proceeding steadily. A significant sign of its acceptance is the almost complete absence of attempts to formulate electrical theories not based upon electrons.

The translation of this work into German and Italian goes to show that its distinctive features are also recognised abroad.

I have embodied some of the latest contributions to the theory in an Appendix.

I wish to thank the numerous reviewers for their

uniformly friendly judgments and suggestions, and especially Mr. Joseph A. Gillott, Dr. T. M. Lowry, and the expert of the Chemists' Club of New York, for pointing out certain errors and omissions.

E. E. FOURNIER D'ALBE.

CHAPELIZOD, *December* 1907.

AUTHOR'S PREFACE

TO THE THIRD EDITION

LAST year's electrical progress has chiefly taken the directions of electro-chemistry, radio-activity, and spectroscopy. The most important conclusions of these researches have been embodied in the Appendix.

The question of the Hall effect has not yet been satisfactorily settled. The hypothesis of the existence of positive electrons has been lately rendered somewhat more probable, notably by the researches of Wood and the younger Becquerel, but as these are open to several interpretations I have not considered it advisable to depart from the unitary theory of conduction as developed by Lorentz.

It is satisfactory to note that our ideas of atomic and electronic dimensions, masses, and charges are becoming more precise. It appears that the

charge of the electron is more probably above 4×10^{-10} electrostatic units than below that value; but nothing is gained by discarding Thomson's figure until a higher one is definitely established.

E. E. FOURNIER D'ALBE.

DUBLIN, *August* 1909.

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THE ELECTRON THEORY

CHAPTER I

INTRODUCTION

The object of this work is to place before the reader a concise and connected account of the new theory of electricity and magnetism, which, though, generally accepted, has as yet hardly found its way into the elementary textbooks. The new theory gives us a grip of electrical and magnetic phenomena which was quite unattainable so long as we knew nothing about the real nature of electricity. We now know that electricity is a kind of subtle fluid consisting of *electrons*, or very small corpuscles, some thirty thousand times smaller than the atoms of ordinary matter. The electron theory is that theory which reduces all electric and magnetic phenomena to the distribution and motion of these electrons. To gain a clear grasp of the nature and properties of the electron is, therefore, henceforth the first step in the knowledge of electricity. In presenting it to the reader, my first objects will be simplicity and

lucidity, and I hope to enable those readers whose mathematical attainments have not transcended the elementary rules of algebra to master the essential principles of the science, so as to be able to apply them to practical problems.

A theory has two functions—one is to register a large number of isolated facts in due order, and the other is to give us an insight into their connection with each other, so as to be able to deduce one from the other and to predict new facts and produce effects hitherto unknown. The electron theory fulfils both these functions in a manner which no previous theory of electrical phenomena has been able, even remotely, to approach.

In no branch of human knowledge have greater difficulties been encountered in framing an adequate theory than in the science of electricity. The bewildering variety of the phenomena, the constant stream of new facts and discoveries, the revolutionary character of many of them, and the intangible nature of the agent itself, combined to render the formulation of an all-embracing theory difficult. But the reward of arduous work has been correspondingly great. To-day we know more about the atom of electricity than we do about the atom of ponderable matter. We can contemplate it as a centre of force producing the old phenomena of the pith ball and the gold leaf and the rubbed glass rod. We see it in swift motion in the vacuum tube, and in slow

motion along the current-bearing wire, now no longer the inscrutable mystery it was ten years ago. We observe its surgings to and fro in the alternating current, and follow the waves it emits across space into the wireless receiver. We imagine its orbital motion round the atom it clings to, and the vista of magnetic phenomena flashes into view. We watch it dragging along that same atom through the electrolytic cell, and gain an insight into the secrets of chemistry such as seems likely to remodel that whole vast science. Not content with having annexed practically the whole of physics and chemistry, our new conception launches out into unexplored fields. It hints at the transmutation of the elements, the constitution and destruction of matter, the explanation of inertia, and an electrical theory of mechanics as an answer to the all-pervading influence hitherto exercised by mechanical conceptions. The electron theory, this latest and widest of scientific generalisations, is the fitting reward of 150 years of laborious research. A somewhat unusual circumstance attending its victory lies in the fact that it supplements rather than displaces the older theories. It has something of Franklin's one-fluid theory about it, inasmuch as it links all electric phenomena with the distribution and motion of a kind of gas possessing a pressure and an atomic structure. It supplements the analytical speculations of Ampère and Weber by providing the

necessary material substratum, and fits itself, lastly, into the ether theories of Maxwell and Hertz by telling us what is at the ends of the lines and tubes of force whose distribution and motion have played such a useful and almost exclusive rôle in the electromagnetic theory of yesterday.

This may partly account for the almost ominous silence with which the new theory has made its appearance in the electrical world. It has not been heralded by a flourish of trumpets, nor has it been received with violent opposition from the older schools. No one man can claim the authorship of it. The electron dropped, so to speak, into the supersaturated solution of electrical facts and speculations, and furnished the condensation nucleus required for crystallisation. One after another the molecules—the facts of electricity—fell into line, and one department of electrical science after another, crystal on crystal, clicked into its place, dispersion first, then electrolysis, then gas discharges, then radium rays, then metallic conduction, and, lastly, magnetism.

Nor is the crystal fully shaped yet. The electron theory has to absorb every detail, to assimilate the vast store of accumulated facts, to find a place in the edifice for every loose brick, to strengthen every weak place,—and there are still many, though they diminish daily in number and importance.

Our textbooks, always shy of innovations, must

gradually be brought round to the newer views. They must be given courage to speak about "electricity"—a word they have lately been chary of using, as it conveyed no meaning! The scientific electrician had become accustomed to deal with "electrification" or "electric quantity" as the only thing he knew, and to leave the use (and misuse) of the word "electricity" to the layman. The electrical theorist found a refuge in differential equations involving pure quantities, and dealt with them by mathematical rules, *alias* generalisations from the results of experiments in counting. The practician, having no such vast experience in processes of counting, but having instead a close familiarity with the behaviour of bodies and substances, also derived from vast experience, found that the habits of thought thus acquired did not assist him towards an intimate knowledge of the nature of electricity. He did his best by annexing Faraday's semi-material "lines of force," and applying them to problems of induction with truly astonishing industrial results. What he will do when he gets a grip of the electron we can only faintly guess.

Will the electron theory be final, or will it in turn be superseded by another theory? This is a very pertinent question, but more pertinent for the textbooks and professors than for the research worker or the practician. In one sense, no theory is final. A final theory is the death of science. When a man

frames a theory he is delighted to find it confirmed everywhere. When he comes across a case where it fails, he should be equally delighted, for he has found a really new truth, a truth not contained implicitly in his theory. But a theory may be final in the sense that Newton's gravitational theory is final. That theory applies to all ponderable matter at distances beyond molecular range. The electron theory applies to all electrified and magnetised matter, and has even been made to include gravitation as a special case. If it can bring the whole of electrical and magnetic phenomena into one well-ordered system, not to speak of chemistry and mechanics, it will be of permanent and incalculable value. If it succeeds in analysing the chemical atom, it will abolish one of those puzzling complexities of which the human intellect is so persistently impatient—the variety of the chemical elements. Progress in this direction will tend to unify physical science, and leave the road free for advance into those realms of infinitely greater complexity which harbour the phenomena of life.

CHAPTER II

THE ORIGIN AND DEVELOPMENT OF THE ELECTRON THEORY

THE first serious attempt to formulate a theory of electricity as distinct from a vague guess or a provisional hypothesis was made by Benjamin Franklin, who announced his one-fluid theory in 1750 in his letters to Collinson. He supposed that a subtle fluid or "electric fire" was distributed throughout the world, that it was attracted by ordinary matter, but that its particles repelled each other. The fluid can penetrate metals, but not insulators. Being, however, attracted by insulators, like glass, it accumulates at the surface only. To explain why a glass rod should be electrified by friction, Franklin made the fantastic assumption that the glass, being expanded by the heat, takes up more than its ordinary share of the fluid, and seeks to give it up again on cooling. This explanation seems forced; but it should be remembered that frictional electrification is, up to the present day, the least explained of all electric phenomena.

Franklin's theory, in order to be consistent, had

to assume that atoms of ordinary matter repel each other, and this was at once perceived to be at variance with the facts of gravitation and cohesion. But how close the agreement is between Franklin's one-fluid theory and the electron theory may be seen by putting the latter into Franklin's language as follows:—

"Through all corporeal nature *one* subtle matter is distributed, which contains the reason and cause of all electric phenomena. The particles of this fluid repel each other. All matter in its normal state contains a fixed quantity of this fluid. If any portion of matter is deprived of some of this fixed quantity, it attracts the fluid with a force proportional to the amount it has lost, and repels another portion of matter that has suffered a similar loss. All electric phenomena are due to the distribution and motion of the particles of the fluid."

Franklin's theory failed on the question of conductors *v.* insulators. He supposed that conductors could take up any amount of the fluid and store it throughout their substance, while insulators could only store it on their surfaces. The modern version is that conductors take up an additional amount of the fluid, within limits depending upon circumstances, and store it on their surfaces only. On the other hand, they cannot be deprived of more than the "fixed quantity" mentioned above. But the fundamental difference between the old and

the new views lies in the use of the words "positive" and "negative." In an evil hour the electricity derived from rubbed glass was called positive electricity, and the electricity derived from amber was called negative. The fact that the two electricities neutralised each other made the terms justifiable; but there was nothing to indicate which kind was the real and only fluid. It was assumed, at haphazard, that the glassy electricity was *the* fluid, and for 150 years all algebraic signs continued to be placed in accordance with that idea, and they continue so to the present day. Thus we speak of the "positive pole" of a battery as the pole from which the glassy electricity appears to flow, whereas we know now that if there is a flow at all it is *towards* that same pole, the flow in the reverse direction being insignificant in comparison. This fundamental difference is not apparent in our Franklinian version of the electron theory above; but it makes a very radical difference, and places a serious obstacle in the way of popularising a logical terminology. We have to learn that the "negative" electricity is *the* electricity, and the negative current *the* current. In the present period of transition, great care must be exercised to prevent confusion, and a way of doing so will be indicated later on (p. 86).

The one-fluid theory, as we have seen, did not succeed very well in explaining frictional electrification. Hence, when, in 1759, Symmer brought

out his two-fluid theory, it met with a wide acceptance, and continued in active possession until the phenomena in vacuum tubes began to exhibit an essential difference between positive and negative electrification.

The fluid theories were marvellously ingenious, considering the poverty of the materials upon which they were based. In the whirl of subsequent discoveries, they were like guiding stars faintly visible through a mist. Sometimes they were almost lost sight of in the crowd of new facts and speculations; but other forces were at work to bring order into the chaos. The greatest force was the advance in measurement. Lane's unit jar in 1781 was the true beginning of electrical science, if we accept the dictum that "Science is measurement." Coulomb's torsion-balance (1784–1788) gave us two new inverse-square laws in addition to the Newtonian one of gravitation. The mathematicians had begun to handle these new laws with fruitful results when the scientific world was startled with Galvani's frog in 1791, and kept in a state of agitation by the long controversy between Volta and Galvani concerning a third fluid, which the latter persisted in calling "animal electricity." Volta's pile in 1799, followed by Cruikshank's and Davy's electrochemical work, closed the eighteenth century, which left the theory of electricity in wild confusion, and its devotees torn by endless dissension.

This state of things, coinciding with the Napoleonic wars, accounts for the temporary collapse of electrical research in the new century. There is hardly anything to chronicle between 1800 and 1820, except perhaps young Grotthus's hypothesis (1805) and Poisson's mathematical treatment of electric and magnetic potential (1811), based upon Coulomb's laws. In revenge, the next twenty years brought forth a flood of discovery such as has rarely been crowded into so short a time, and remained unequalled until the revolution of 1896. Ampère, Oerstedt, Biot, Savart, Seebeck, Ohm, Peltier, Faraday, Weber, and Joule, all fall within this period. Truly a galaxy of genius and phalanx of philosophy.

Oerstedt, in 1820, threw the first bridge between electricity and magnetism. Seebeck connected electricity with heat, and Faraday linked the phenomena of electricity and motion, and laid the foundation of the two great modern theories of electricity and magnetism: Maxwell's ether theory and the electron theory. The latter foundation he laid, however, unwittingly, being personally disposed to consider rather what happened in the medium between bodies than what happened in the bodies themselves.

It is interesting, in the light of the modern electron theory, to read some passages from Weber's *Werke*, where he foreshadows the atomic theory of electricity. Thus in vol. iv. p. 279, we read:

"Considering the general distribution of electricity, we may assume that an electric atom is attached to every ponderable atom." And again, p. 281: "Let *e* be the positive electric particle; let the negative one be equal and opposite, and let it be denoted by $-e$. Let only *the latter* have a ponderable atom attached to it, and let its mass be thereby increased to such an extent that the mass of the positive particle vanishes in comparison. We may then regard the particle $-e$ as stationary, and only the $+e$ as revolving round $-e$." [I have italicised the words which show that Weber's conception is exactly the reverse of the modern one.] He proceeds: "The two dissimilar particles, being in the molecular state of aggregation described, then represent an Ampèrian molecular current, for it can be shown that they fulfil the assumptions made by Ampère concerning his molecular currents." Finally, on p. 292: "The *vis viva* (*lebendige kraft*) of all the molecular currents contained in the conductor increases, while the current passes through in proportion to the resistance and to the square of the current intensity."

Substitute "electrons" for "molecular currents," and you have nearly the modern view of metallic conduction.

The most important dates in Faraday's career were 1831 and 1833. In the former year he discovered electromagnetic induction, and did for a

varying current what Oerstedt had done for a steady one—viz. established the link between electricity and magnetism. This discovery naturally predisposed him to devote his attention to the happenings in the dielectric medium rather than the conducting substance. And yet he made, two years after, a discovery of transcendent importance which was bound sooner or later to lead up to an atomic theory of electricity. It was that whenever two metals or other elements of the same valency are deposited or evolved in the electrolytic cell, the amounts of electricity consumed, as measured by Lane's unit jar or other instrument, are inversely proportional to the atomic weights of the elements. Or, in other words, that the electricity attached to every atom of a given valency is the same, and that if a metal is divalent its atom is associated with twice the usual atomic quantity of electricity.

Commenting upon this discovery in his Faraday lecture, Helmholtz said: "If we accept the hypothesis that elementary substances are composed of atoms, we cannot avoid the conclusion that electricity, positive as well as negative, is divided into definite elementary portions which behave like atoms of electricity."

James Clerk Maxwell, who, following in Faraday's footsteps, worked out a beautiful and successful theory based upon the properties of the medium, also saw the force of this conclusion, without, how-

ever, being able to follow it up owing to the lack of experimental data. In the first edition of his "Electricity and Magnetism," published in 1873, he says (p. 312): "Suppose, however, that we leap over this difficulty by simply asserting the fact of the constant value of the molecular charge, and that we call this constant molecular charge, for convenience of description, one atom of electricity." Later on, however, he adds: "It is extremely improbable that when we come to understand the true nature of electrolysis we shall retain in any form the theory of molecular charges, for then we shall have obtained a clear basis on which to form a true theory of electric currents, and so become independent of these provisional theories."

Maxwell's vision here was clouded, for the theory "of molecular charges" now holds the field in undisputed possession, after decisive victories in four different quarters where its attacks were little dreamt of in 1873.

The very next year an Irish physicist, G. Johnstone Stoney, at the Belfast meeting of the British Association, drew attention to this "atom of electricity" as one of the three fundamental physical units of nature (the others being the velocity of light and the constant of gravitation), and gave an approximate calculation of its value. He said:[1]

[1] See *Scientific Proceedings* of the Royal Dublin Society, Feb. 1881, p. 54. *Philos. Mag.*, May 1881, pp 385, 386.

"Finally, Nature presents us in the phenomena of electrolysis with a single definite quantity of electricity, which is independent of the particular bodies acted on. To make this clear I shall express 'Faraday's Law' in the following terms which as I shall show, will give it precision—viz. for each chemical bond which is ruptured within an electrolyte, a certain quantity of electricity traverses the electrolyte which is the same in all cases. This definite quantity of electricity I shall call E_1."

He calculates the actual charge by dividing the quantity of electricity required for the electrolysis of 1 c. cm. of hydrogen by the number of hydrogen atoms in 1 c. cm. as given by Loschmidt, and finds 10^{-20} "ampères" (now called absolute electromagnetic units of quantity). This figure compares well with the latest value for the electron—viz. $1{\cdot}1 \times 10^{-20}$ E.M. units.

In 1879 followed Crookes's epoch-making experiments on the mechanical properties of those mysterious vacuum discharges called cathode rays by Goldstein, and studied by Plücker and Hittorf since 1859. Crookes, pushing the vacuum to the furthest attainable point, and leaving in the tube only one-millionth of the air originally contained in it, obtained what he called "radiant matter" in a fourth state, superior in dilution to the gaseous state, and marked by a still further disappearance of differentiating qualities such as is observed in

passing from solid to liquid and from liquid to gas. He actually constructed a little windmill driven by a torrent of electrons, of the real "electric fluid" as we now know it, without, however, quite realising the tremendous feat he had accomplished. His opinions and theories were smiled at as being too "grossly material," and the discoverer had to wait twenty years before they were brilliantly confirmed.

The same year that witnessed Crookes's demonstrations before the Royal Society saw the realisation of the long-cherished dream of deflecting a current in a conductor by means of a magnetic field. Crookes had deflected his "radiant matter" by a magnet, and so what more natural than to expect that a magnet should deflect the same matter when picking its way through the substance of a metal! This was accomplished at last by Hall of Baltimore, by bringing a very thin film of gold into a strong magnetic field, and finding that the electricity tended to make its way out by the sides when the current was turned on. If this discovery had been followed up with any spirit, the true import of the *negative* current as the real current would have been realised seventeen years earlier than it was. Hall himself observes:[1]—

"If we regard the electric current as a stream flowing from the negative to the positive pole, the phenomena observed indicate that two *currents*

[1] *American Journal of Mathematics*, vol. ii. p. 287, 1879.

parallel and in the same direction tend to attract each other. . . . Whether this fact, taken in connection with what has been said above, has any bearing upon the question of the absolute direction of the electric current, it is perhaps too early to decide."

In the following year Von Ettinghausen actually claimed to prove that the current proceeded from the negative pole with a velocity of a few millimetres per second. This result was, as we shall see, not far from the truth.

Taken in conjunction with the effect produced on light by reflecting it from a magnetised surface, discovered by Kerr in 1875, the Hall effect might have led very close to the modern electron theory, but for the difficulty of distinguishing between forces on electricity and forces on conductors. Without any idea of the density or inertia of the particles of electricity, all quantitative deductions necessarily remained as vague as Franklin's original "electric fire."

That avenue being barred, electric research took other directions. One of the most fruitful of these was electrochemical research, which, since Faraday's fundamental discovery, had occupied a school by itself, cultivating but little intercourse with the rest of the electrical world. Hittorf, Clausius, and Kohlrausch had, with infinite patience, traced the migration of the ions through the liquid in the electrolytic cell, discovered their mutual independence, and

formulated the theory of ionisation, culminating in the memorable announcement by Arrhenius in 1884 that at infinite dilution *all* molecules of. the electrolyte would be dissociated and free to obey electric forces. This discovery, together with van't Hoff's work on osmotic pressure, formed the foundation on which Ostwald and Nernst have since been able to raise the imposing edifice of the chemistry of ionisation.

Meanwhile, Maxwell's electromagnetic theory was radiating out from Cambridge, and gradually attracting to itself the leading thinkers of the Continent, who felt the inadequacy of the mathematical theories of Weber, Clausius, and Riemann, based upon action at a distance between charged points. Maxwell's successor at Cambridge, J. J. Thomson, took his first step towards the modern corpuscular theory of electricity in the light of Maxwell's views of electromagnetic energy by calculating, in 1881, the "quasi-inertia" possessed by a charged body in virtue of its charge alone.

But the doubts engendered by the two main lines of thought were removed with dramatic suddenness by a few simple experiments made by Hertz, at Bonn, in 1888. He proved that electric force has a finite rate of propagation, and that, if a body is charged, the field of force around it does not pervade all space instantly, but takes a certain time—very short, but still measurable—to reach a distant

point. The speed was found to be the same as that of light—viz. 186,000 miles per second.

This momentous discovery turned the tables completely on the theories of instantaneous action at a distance, and enthroned Maxwell's theory in every Chair in Europe and America. For half a generation after those experiments men were feverishly engaged in testing dielectrics, and making them convey waves of electromagnetic force, the wave of research itself culminating in the triumphs of wireless telegraphy.

In the struggle for the mastery of the dielectric, the harmless necessary conductor was in sore danger of being lost sight of altogether. But already there were indications of the dawn of a new light proceeding from the vacuum tube—a piece of apparatus which, owing to its many vagaries, had acquired an evil reputation as a kind of theory-trap, and had for some time been shunned by all but the most reckless or courageous pioneers. Arthur Schuster was the first to break distinctly new ground, by calculating, with the aid of the magnetic deflection, the ratio of the charge to the inertia possessed by what he, rather unfashionably, called the cathode-ray particles. This ratio came out very high, indicating that either the charge must be high or the mass very small. Every one thought there was something wrong about this measurement, especially when, in 1893, Lenard succeeded in persuading the

rays to pass out through an aluminium "window" into the open air, and proclaimed them, on the strength of their absorption, to be composed of ether waves. We now know that Schuster was right and Lenard wrong; but it took five years of controversy before Lenard gave way before an avalanche of new facts, and finally surrendered.

Towards the end of 1895 the world was startled by the announcement that a professor in Würzburg had discovered rays which could penetrate the human body and show up the bones as shadows. This discovery, made by Röntgen by means of a vacuum tube, converted the latter from being the most despised into being the most universally popular of scientific instruments.

In the nineteenth century four epochs stand out as of transcendent importance in the life-history of the science of electricity. They are 1820, 1833, 1888, and 1896. In 1820, with Oersted, Ampère, Biot, and Savart, the twin sciences of magneto-electricity and electro-dynamics started into being. In 1833 Faraday linked them with chemistry. In 1888 Hertz annexed the ether and confirmed Maxwell's theory; and finally, in 1896, the electron theory was enthroned above all others as their culmination and fulfilment, with almost equal suddenness and with much less opposition than that which Maxwell's theory had encountered.

In that year, Zeeman, of Leyden, discovered that

the spectrum of the light from a sodium flame could be modified by a powerful electromagnet, the lines being doubled when seen in one direction and trebled when seen in another. This phenomenon, mysterious at first sight, was found to be fully explained by a theory formulated by H. A. Lorentz sixteen years before—a theory which reduced the action of matter on light to the presence of minute charged corpuscles revolving round the atoms.

The same year also saw the discovery of uranium radiation by H. Becquerel. The vast significance of these discoveries was perceived in the following year, when J. J. Thomson succeeded in determining the ratio of the charge to the mass of the cathode-ray particles, and, to his great surprise, found this ratio to be identical with that of the Lorentz corpuscles.

Discoveries now followed in rapid succession. Rutherford extended the corpuscular theory to atmospheric electricity. The Curies discovered radium and its radiation of electrons, and then proved that radium emits heat and charged particles without cessation. Everywhere, and sometimes in the most unexpected quarters, the same electron—the same fundamental quantity of "negative" electricity—was rediscovered. Schuster, Simon, Kaufmann, Townsend, Wilson, Riecke, Drude, and a host of others busied themselves with investigating its properties; and one realm of electrical science

after another was annexed to the all-embracing electron theory. Abraham, Sommerfeld, Bucherer, Wien, Larmor, Langevin, and Lodge extended the theory, both mathematically and experimentally, and reconciled it with the fundamental equations of Maxwell and Hertz. Nor is the work yet completed. Every day brings new material and new conquests. A fresh zest has been given to research in all branches of electricity, and hosts of workers are engaged in pushing the new conceptions to their logical conclusion. When they have reached the engineers and practical men, new discoveries and inventions of far-reaching import may be confidently anticipated.

CHAPTER III

THE ELECTRON AT REST

1. *Properties of the Electron.*—The electron is the smallest electrified body capable of separate existence. Its mass is approximately $0{\cdot}61 \times 10^{-27}$ grammes. Its radius is roughly estimated at 10^{-13} cm. Its charge consists of what has hitherto been called "negative" electricity—*i.e.* the electricity possessed by a stick of sealing-wax when rubbed with wool.

The fundamental property of the electron which distinguishes it from ordinary matter is that it repels another electron, instead of attracting it, as two pieces of matter would do. When one electron is placed at a distance of 1 cm. in a vacuum from another electron, it repels it with a force of $1{\cdot}16 \times 10^{-19}$ dynes, a force which is something like a quadrillionth of a pound. This force may appear excessively small, but, as a matter of fact, it is enormous. It is more than a trillion trillion times (more precisely, 10^{43} times) greater than gravitational attraction, which accounts for the weight of bodies on the earth's surface and the motion of

the heavenly bodies. How enormous it is may be realised by the following imaginary experiment. Let two masses, M M_1 (Fig. 1), say of lead, weighing 1 gramme each, be placed 1 cm. apart. They will attract each other with a force of $6{\cdot}6 \times 10^{-8}$ dynes, a force quite too small to be measured by any known instrument. But now let 2 grammes of pure negative electricity, E E_1, made up of electrons, be placed side by side at the same distance. They will repel each other with a force of $31{\cdot}4 \times 10^{34}$ dynes, or 320 quadrillion tons!

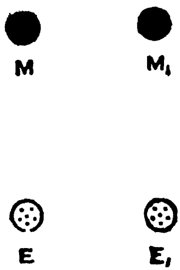

FIG. 1.

Even if they were placed, one at the North Pole of the earth, and the other at the South Pole, they would still repel each other with a force of 192 million tons, and that in spite of the fact that the force decreases with the square of the distance. That force would be capable of imparting to each of these grammes of pure electricity a velocity equal to that of light in less than a millionth of a second, and would only fail to do so owing to the fact that the inertia of each electron becomes infinite, or nearly so, as it approaches the velocity of light. In any case, it is obvious that the experiment must remain purely imaginary.

We obtain somewhat less appalling figures if we suppose there to be only 1 gramme of pure

electricity, and a single electron placed at 1 cm. from it. The force is still 194 million dynes; but if we separate the two bodies, as before, by the distance of the earth's axis, the force reduces itself to the inappreciable amount of $1 \cdot 2 \times 10^{-10}$ dynes. Small as this force is, it must be remembered that the mass at one end of its line of action has been reduced in the same proportion, so that the single electron will be projected just as before with the same explosive velocity. We should have to remove it as far as the sun to reduce the acceleration to something like manageable proportions, and even at that enormous distance ($=1 \cdot 53 \times 10^{13}$ cm.), the force exerted by 1 gramme of pure electricity on earth upon all the free electrons in the sun would suffice to impart to them a velocity equal to that of light in 20 seconds.

It is quite evident from the above considerations that in all ordinary electrical phenomena, we are dealing with a very minute quantity of free electricity. Let us attempt to arrive at some idea of its amount.

2. *Electrons and Matter.*—We deduce from the laws of electrolysis that every atom of matter is capable of temporarily uniting with a definite quantity of electricity, which is exactly proportional to its chemical valency, but is otherwise independent of the nature of the element. Thus in the electrolysis of hydrochloric acid every atom of

chlorine brings to the anode a definite quantity of negative electricity, a quantity which we can measure with a galvanometer. Knowing the weight of the chlorine evolved and the weight of the atom of chlorine (as we do), we can find by a simple calculation that the quantity transported by each atom is, as nearly as we can make it out, just one electron. We therefore conclude that every atom of chlorine in the electrolytic cell has one electron somehow associated with it, but associated in such a manner that it is ready to be detached when a finite force is brought to bear upon it. In the normal state the chlorine atom does not carry this electron with it, and it is therefore uncharged.

Other elements—such as hydrogen and the metals—are also uncharged in the normal state. Each atom contains a number of electrons, but their electrical action is compensated by some force within the atom which, for lack of a better term, we may call "positive electricity"; but each of their atoms, when placed in an electrolytic cell and subjected to electric force, is liable to temporarily lose an electron—or two electrons if the element is divalent—and thereby become "positively" charged.

We have, therefore, reason to suppose that in any uncharged lump of a divalent metal—say a ball of copper—there are at least twice as many electrons as there are atoms. Since the connection

between the atoms and these electrons is not rigid, we may suppose that this proportion is liable to variations. When the electrons are in excess of the usual number, we find that the ball is negatively charged; when there is a deficiency, the ball is positively charged. Having seen above what enormous forces the electrons are capable of exerting upon each other, we have no difficulty in conceiving adequate causes for such variations.

Now, when the balls are thus charged, it is found that the electrons, or the positively charged atoms, in spite of their mutual repulsion, do not shoot out of the metal into the surrounding air. They traverse the metal with very little friction, but experience a great resistance at the boundary between metal and air. They therefore take up a position of equilibrium on the surface itself, and stay there, leaving the interior of the metal uncharged.

A B

FIG. 2.

Next, suppose that two small copper balls, A and B, are suspended side by side by insulating fibres 1 m. long (Fig. 2). Let them be negatively charged, so as to repel each other, and remain 1 cm. apart. Then the force between them is easily proved to be $\frac{1}{200}$th part of their weight. If their radii are 1 mm. each, what number of free electrons will suffice to produce the necessary repulsion?

The following data are easily calculated:—

Volume of each ball	$4 \cdot 2 \times 10^{-3}$ c.cm.
Weight (density 8·93) . . .	$3 \cdot 75 \times 10^{-2}$ gr.
Force of repulsion	$1 \cdot 87 \times 10^{-4}$ gr.
	$= 0 \cdot 184$ dynes.

This is the force that would be exerted by 1260 million electrons upon an equal number placed at a distance of 1 cm. in air. This is, then, the number of free electrons in each ball.

The number seems exceedingly high, but we shall soon see that it is but an insignificant fraction of the total available electrons present.

According to the most trustworthy estimates, the total number of atoms contained in a cubic centimetre of solid copper is about one quadrillion, or $1 \cdot 23 \times 10^{24}$. Now each of our balls having a volume of $4 \cdot 2 \times 10^{-3}$ c. cm., would contain $(1 \cdot 23 \times 10^{24})(4 \cdot 2 \times 10^{-3})$ atoms, and double that quantity of detachable electrons, or 10,300 trillion. The ratio of detachable electrons to extra electrons is therefore

$$\frac{10{,}300 \text{ trillion}}{1{,}260 \text{ million}} = 8 \text{ billion.}$$

Hence if, for every eight billion combined electrons in the copper, we add one extra electron, we obtain the necessary force of repulsion. Since a neutral atom deprived of an electron repels another such atom with the same force as that which exists between two electrons, we may also produce the same

repulsion by removing from each ball one electron out of every eight billion that are in it; they then repel each other by virtue of their positive charges.

On account of the intensity of the forces called into play, it is found practically impossible to remove more than about one-millionth of the detachable electrons, or add more than that proportion to those already there. This explains why the charging or discharging of a body produces no perceptible difference in its weight. If, however, by some special contrivance, electrons or positive atoms are continually discharged from a body, the body is gradually disintegrated. This happens to the cathode in a vacuum tube and to the positive carbon in the arc lamp.

We may now formulate the forces between electrons and positively charged atoms a little more precisely as follows: (*a*) Every electron placed at a distance of 1 cm. from another electron repels it with a force of $1{\cdot}16 \times 10^{-19}$ dynes. (*b*) Every neutral atom from which one electron is removed repels any similar atom placed at a distance of 1 cm. with the same force—viz. $1{\cdot}16 \times 10^{-19}$ dynes. And, on the other hand, (*c*) every electron attracts every neutral atom from which one electron is removed, when placed at a distance of 1 cm. from it, with the same force—viz. $1{\cdot}16 \times 10^{-19}$ dynes, or if two, three, &c., electrons have been removed, with a force two, three, &c., times that amount. (*d*) All these forces vary in-

versely as the square of the distance, unless that distance is so small as to become comparable with the dimensions of the atom (*i.e.* 10^{-8} cm.).[1]

It follows from the law of attraction that an electron cannot be removed from a neutral atom without a very great force as compared with its mass. The attraction between them is the strongest cohesive force we know, and if it accounts for cohesion to any perceptible extent, the force required will at least be that necessary to rupture the metal or other substance. If the law of attraction holds good down to molecular dimensions, which are of the order of 10^{-8} cm., we can calculate the force between an electron and the atom it is being induced to leave. We need only divide the attraction at 1 cm. by the square of the distance, or 10^{-16}. The force then becomes

$$\frac{1{\cdot}16\times 10^{-19}}{10^{-16}}, \text{ or } 1{\cdot}16\times 10^{-3} \text{ dynes.}$$

This force, acting upon an electron for one second,

[1] According to the electron theory of gravitation (W. Sutherland, *Phil. Mag.*, Dec. 1904), the attraction between opposite charges is greater than the repulsion of similar charges in the ratio of $(1+10^{-43}):1$, thus accounting for a very small resultant attraction. In the electron theory the attractions and repulsions are, like gravitational force, independent of the manner in which the intervening space is filled up. Matter free from electrons would have no electrical effect whatever, and can be theoretically replaced by pure ether in all electrical problems. The effects hitherto ascribed to the "specific inductive capacity" or dielectric constant of the medium are accounted for by the charges which that medium contains.

would give it a speed measured by the ratio of the force to the mass, or—

$$\frac{1\cdot16\times10^{-3}}{0\cdot61\times10^{-27}} = 1\cdot9\times10^{24}\,\frac{\text{cm.}}{\text{sec.}}$$

This result shows that any electron coming within the radius of molecular action would be instantly captured and absorbed by a positively charged atom. Since the number of free electrons in the universe is by all accounts strictly equal to the number of positively charged atoms, or, rather, valencies of such atoms, it is difficult to conceive how it is possible for any electrons to have remained free at all. Were they all to become absorbed, as they some day will be most likely, there would be no electric action of any kind, and, we suspect, no chemical action either, and two sciences would become superfluous.

To understand why we have escaped that fate, we may take an analogy on a very large scale. The force exerted by the sun on the earth is some four trillion tons. Yet the earth does not fall into the sun, on account of the centrifugal force generated by its own velocity. Let us see what velocity would be required to keep the electron from being absorbed by the atom. The force to be counterbalanced is, as we have seen, $1\cdot16\times10^{-3}$ dynes. The centrifugal force of a body of mass m describing an orbit of radius R with a velocity v is $\frac{mv^2}{R}$. Substituting for

m the mass of the electron ($0{\cdot}61\times10^{-27}$ gramme), and for R its distance from the centre of the atom (10^{-8} cm.), we get—

$$1{\cdot}16\times10^{-3}=\frac{0{\cdot}61\times10^{-27}\times v^2}{10^{-8}}$$

which gives $v=\pm1{\cdot}38\times10^8$ cm. per second. This orbital velocity of the electron, though large, is quite conceivable, inasmuch as it is still less than $\frac{1}{200}$th the velocity of light (the utmost attainable speed). Knowing the size of the orbit, we can calculate the number of revolutions it makes per second. This is $2{\cdot}2\times10^{15}$ or 2200 billion. As we shall see below, the revolving electron sends out ether-waves into space with the velocity of light (3×10^{10} cm. per second). Hence the length of these waves is

$$\frac{3\times10^{10}}{2{\cdot}2\times10^{15}},\text{ or }136\times10^{-6}\text{ mm.}$$

This wave-length is about one-third of that of the shortest visible light-waves. The waves emitted by the electron are thus waves of ultra-violet light. Now, by Kepler's law we can easily find what distance between electron and atom would give us any required wave-length. By that law the squares of the periods of revolution are in the same ratio as the cubes of the distances. If, therefore, we make the distance 10^{-7} cm. instead of 10^{-8}, we increase the distance ten times, and the cube of it 1000 times. The wave-length will, therefore, be increased in the

ratio of $\sqrt{1000} : \sqrt{1}$, or 31·6 times. This gives for the wave-length of the light emitted by the electron in its new orbit. the value 4300×10^{-6} mm. This light is also invisible, being about six times longer in wave than the most extreme red light of the spectrum. It is "infra-red." An intermediate value of the distance will give visible light. The yellow light of sodium would require a distance of $2{\cdot}66 \times 10^{-8}$ cm. between the electron and the atom.

Of course, the electrons in a solid metal have widely varying velocities, and hence they give a continuous spectrum when the average velocity is high enough—*i.e.* when the body is hot enough; otherwise they radiate heat-waves of great length and small energy, in accordance with the law of exchanges.

The above considerations show that we must conceive a metal to be composed of a mass of metallic atoms pretty closely packed, so that the electrons, in their constant vibration due to a finite temperature, are often and easily exchanged between them. They therefore pass from one atom to another with comparatively little frictional loss of energy. The metals are called "good conductors of electricity" on account of this property.

In other bodies, such as glass, ebonite, shellac, quartz, oil, indiarubber, and porcelain, there are only very few electrons sufficiently free to pass from one atom to another. If they surround a metal, they

prevent the electrons escaping from it even under the influence of a considerable force. Hence they are called "insulators."

That they do contain their due ratio of electrons to atoms is shown by the strain to which an electric force subjects them, and by the influence they exert upon light which passes through them.

A vacuum, offering, as it does, no resistance to the motion of an electron, is, in that sense, a perfect conductor; but not in the accepted electrical sense. To conduct electricity, a body must be able to provide carriers for its connection. These carriers are the electrons and positive atoms, with or without extra matter attached to them. The vacuum, containing no such carriers, is *a perfect insulator.* This conflict of characteristics warns us that our definition of a good conductor is not complete. To conduct electricity well, a body must contain free electric charges, and offer but a slight resistance to their motion in the direction of the electric force. These free electric charges are either single electrons or portions of neutral matter associated with positive or negative charges. A good conductor is one which contains a large number of free electric charges (called "ions"), and offers but slight resistance to their motion. The "conductivity" of any material is defined, in accordance with the electron theory, as the number of ions in unit of volume multiplied by the steady speed acquired by them under the influence

of unit electro-motive force. In accordance with this definition, we must declare the ether to be a perfect insulator.

3. *Distribution of Free Charges.*—We have seen that a metal consists of a vast number of atoms (about one quadrillion per cubic centimetre), and about double that number of electrons. These are in rapid motion, and the ether waves they emit in consequence of that motion constitute their radiant heat. Every body radiates heat, unless it is at the absolute zero of temperature (−273° C.), and it is enabled to do so by the heat it receives in exchange from its surroundings.

In an insulator, the electrons are incapable of moving outside the range of the atoms to which they are attached. An electric force displaces them slightly; but when the force is withdrawn, they return more or less rapidly to their former position of equilibrium.

In a conductor matters are different. The motion of both atoms and electrons is much more violent, and electrons are constantly running free, colliding with atoms and with each other, whirling round atoms, locked up with them, liberated by collision with other electrons or atoms, and starting on the same round over again. This difference between dielectrics and conductors is not as yet fully explained, but several circumstances shed light upon it. In the first place, conductors are usually heavier

than dielectrics. Therefore the atoms are heavier or more closely packed, and the electron is claimed by a greater number of neighbouring atoms. Secondly, conductors, mostly metals, have a low specific heat, which means that a comparatively small amount of heat suffices to give them the molecular velocity corresponding to a given temperature. Hence they radiate and absorb heat-waves readily, and the "exchange" above referred to is more lively in conductors than in dielectrics.

We shall for the present confine our attention to conductors, and more particularly to metals, or to copper as a particularly good conductor.

In this metal it has been roughly estimated that every electron combines with an atom, and is liberated again about a hundred million times per second. For every 5000 seconds which it spends locked in the embrace of an atom it roams free for one second. It is these roaming electrons which produce all the phenomena of conductivity. We may suppose that they constitute $\frac{1}{5000}$th of the total number of electrons in the copper; but this number is very uncertain, and must vary with the temperature and the quality of the metal. The roaming electrons do not constitute an electric charge, since they are balanced by an equal number of positively charged atoms contained in the conductor.

What will happen if a mass of free electricity, such as we have contemplated above, but containing

a smaller and more manageable number of electrons, is brought near a lump of metal containing neither an excess nor a deficiency of electrons?

Obviously, the free electrons in the lump of metal will be repelled, and will make their way as far as they can in the opposite direction. The charged atoms left behind will be attracted, and will crowd towards the mass of electricity. When equilibrium has been attained, the point of the conductor nearest the store of electrons will be found to be positively charged, and the point farthest away will be found negatively charged, with a more or less gradual transition at intermediate points, according to the shape of the conductor. This is the well-known phenomenon of "charge by influence," discovered 150 years ago by Æpinus in St. Petersburg.

To keep in touch with reality, it will be well to obtain some quantitative idea of this charge, and to do so we must deal with a larger quantity of electricity than that of a single electron. The most natural procedure would be to make our unit consist of a certain large number of electrons, say a multiple of ten. But this is barred by the uncertainty which still surrounds the precise charge of the electron. J. J. Thomson's latest estimate is $3{\cdot}4 \times 10^{-10}$ "electrostatic units," and this is the value we have assumed throughout our calculations. But in practical measurements the unit is defined as that quantity which, when placed in a vacuum at a distance of

1 cm. from an equal quantity of the same sign, repels it with a force of 1 dyne ($=\frac{1}{981}$ gramme).

Now since one electron or positive atom repels another at 1 cm. with a force of $1{\cdot}16 \times 10^{-19}$ dynes,[1] and the force varies with both masses, the repulsive force of 1 dyne would be produced by $2{\cdot}93 \times 10^{9}$ electrons, or 2930 million.

This quantity of 2930 million electrons (more or less) is what is called the "electrostatic unity of quantity," being derived from measurements of electrostatic force. For the purposes of this work, in which the reader is to be constantly reminded that electricity has an atomic structure, *we shall prefer to call the 2930 million electrons* (the equivalent of one "electrostatic unit" of negative electricity) *a "company" of electrons,* and the same number of charged atoms (or any other objects) a "company" of such atoms or objects. The number 2930 million is for the present assumed to be correct, but it may have to be slightly modified in course of time.

We may now re-state our laws of repulsion as follows:—

(*a*) One company of electrons repels another company placed at 1 cm. from it with a force of 1 dyne.

(*b*) One company of neutral atoms deprived of one

[1] The *dyne* is the force which, acting for one second on a mass of one gramme, produces in it a speed of 1 cm. per second. It is the 981st part of a gramme.

electron each repels another such company at 1 cm. with a force of 1 dyne.

(*c*) One company of electrons attracts a company of neutral atoms deprived of one electron each with the force of 1 dyne.

(*d*) These forces vary inversely as the square of the distance (the distance being large as compared with that between the individual electrons or atoms).

4. *Energy of Position: Potential.*—When motion takes place in spite of a resistance, work is being done. When the motion is steady the force producing it is equal to the force resisting it, and the work is measured by the distance covered. If the resistance encountered between two points is due to contact with intervening matter, the amount of work done in passing from one point to another depends upon the path. Thus, in driving from one town to another, the work is less over a good road than a bad one. If, however, one road is twice as good as another and also twice as long, the total work is the same. The badness of a road is measured by the resistance it offers to the vehicle, and the work is measured by the product of the distance and resistance, so that if the work along two routes is the same, the length of each route must be inversely as its "badness" (resistance).

When the resistance is due, not to intervening matter, but to the repulsion of a distant body, the

work done simply depends upon the distance from that body, and is quite independent of the path traversed. Ignorance of this fact has inspired most of the unsuccessful seekers after perpetual motion.

If the repelling distant body is a point or very small sphere, and a series of concentric spheres are constructed round it, work has to be done on the repelled body to make it pass from one sphere to the next; but no work is required to move it along the surface of any given sphere, since all points on that surface are at the same distance from the repellent body. In passing from one sphere to the next inner one, a certain amount of work must be done. When the repelled body returns to its first sphere, that work is given up again, and can be used to overcome some other resistance. A body thus capable of performing work owing to its position, is said to possess "potential energy," in other words, a potentiality of work. Clearly, the potential energy will be the greater the nearer the body is to the repellent body. But how can the actual amount of the total potential energy be measured? The problem presents one obvious difficulty—the repulsive force extends into infinite space, so that the potential energy would appear to be infinite; that is to say, the repelled body can be made to do work to an infinite extent, for however great the distance to which it may have been repelled, there is still some remainder of repulsion ready to act upon it and make it work.

This argument, though plausible, is vitiated by the fact that the sum of an infinite number of infinitesimal quantities is not infinite, but limited. That this must be so may be illustrated by a few familiar examples. One of them is the old Greek dilemma about Achilles and the tortoise. A tortoise is a mile ahead of Achilles, who starts in pursuit. Achilles runs 100 times as fast as the tortoise, so that when he has run the mile, the tortoise is $\frac{1}{100}$ mile ahead. When Achilles runs that distance, the tortoise is $\frac{1}{10000}$ mile ahead, and so on. So that Achilles will always get nearer the tortoise, but never quite up to it. The solution is that the sum of these quantities

$$1+\frac{1}{100}+\frac{1}{10,000}+\frac{1}{1,000,000}, \text{ \&c.}$$

is a finite number, as is evident when written as a decimal fraction

$$1{\cdot}0101010101 \ldots \ldots \ldots$$

a number which is certainly smaller than 1·0102, and is exactly equal to $\frac{100}{99}$. The tortoise will therefore have gone exactly $\frac{1}{99}$ of a mile when Achilles overtakes it.

Another example is this. If you stand on a bridge over two parallel lines of railway, the rails seem to meet on the horizon. If you stand over one line, the rails, if running straight along an *infinite* plane, will meet in a point on a level with your eyes.

If a train is travelling out along the other line of rails, it will approach the first line as the distance increases. It can never cross it, as the rails are all supposed to be parallel. If the train, therefore, moves on for infinite time it will always be approaching that point on the horizon, but never reaching it. We see, then, that infinities and infinitesimals may often be combined into finite quantities subject to ordinary arithmetic. This may encourage us to tackle the problem of the total potential energy of a repelled body.

For this purpose we will surround the repelling body E with a series of concentric spheres (Fig. 3).

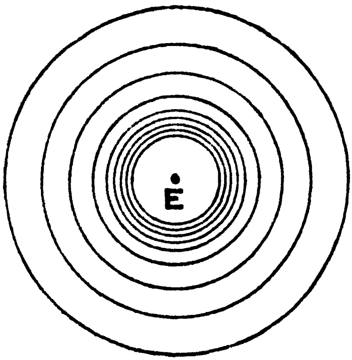

FIG. 3.

The surfaces of these spheres are called "equipotential surfaces," since the repelled body has the same potential energy while it remains in the same surface. We will not draw these spheres at random, but make their successive diameters so that the same amount of work is done in passing from any sphere to the next. Since the force of repulsion varies inversely as the square of the radius, the distance between two successive spheres must vary directly as the square of their

mean radius. At twice the distance, therefore, the equipotential surfaces will be four times as far apart.

Now place a small negatively electrified body, say, a "company" (1 E.S. unit) of electrons, at E and another at a point P. The problem is to find its total potential energy at P—*i.e.* the work that has been done on it to bring it up to P from an infinite distance, or the work that it is capable of doing in retiring to an infinite distance.

To simplify matters, describe a special sphere passing through P, and others with radii twice, four times, eight times, &c., as large, passing through Q, R, S, &c. (Fig. 4). In passing from P to Q, the company cuts a certain number of equipotential surfaces, and this number measures the work done upon it. Let this work be denoted by W. In passing from Q to R, its experience will be precisely similar, except that, the distance between successive surfaces being four times what it was before, the rate of work will be one-fourth. Since, however, the distance traversed is twice as great, the actual work done between Q and R will be one-half that done between

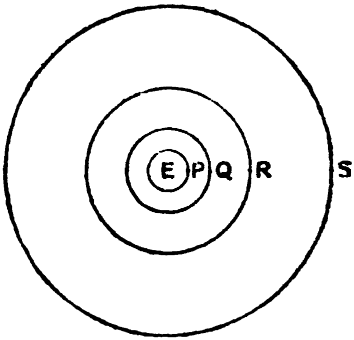

FIG. 4.

P and Q. In the next compartment, the work will be $\frac{W}{4}$ instead of $\frac{W}{2}$, and the next again it will be $\frac{W}{8}$.

Extending this to infinity, the total work done (= the total potential energy) is

$$W + \frac{W}{2} + \frac{W}{4} + \frac{W}{8} + \frac{W}{16} \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot$$

Now, as every one can easily try for himself, the sum of

$$1 + \tfrac{1}{2} + \tfrac{1}{4} + \tfrac{1}{8} + \tfrac{1}{16} + \tfrac{1}{32} \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot$$

to infinity, is just = 2.

Hence the total work is 2 W. This is the potential energy of the company when at P. The potential energy at Q will be

$$2\,W - W = W.$$

At R it is

$$W - \frac{W}{2} = \tfrac{1}{2}\,W.$$

At S it is

$$\frac{W}{2} - \frac{W}{4} = \tfrac{1}{4}\,W.$$

In other words, the potential energies at P, Q, R, S are as

$$2 : 1 : \tfrac{1}{2} : \tfrac{1}{4}$$

or

$$1 : \tfrac{1}{2} : \tfrac{1}{4} : \tfrac{1}{8}.$$

Since the distances are as

$$1:2:4:8,$$

we find that *the potential energy at a point is inversely as the distance of the point from the centre of the repellent body.*

To obtain the actual value of the energy in foot-pounds or other units of work, we need only determine the work done between P and Q and double the amount. If the force at P is 1 dyne, the force at Q must be $\frac{1}{4}$ dyne. If the distance between P and Q is 1 cm., the work must lie between

$$1 \text{ cm.} \times 1 \text{ dyne and } 1 \text{ cm.} \times \tfrac{1}{4} \text{ dyne.}$$

The work of overcoming or exerting a force of 1 dyne through 1 cm. is called "1 erg": hence the work between P and Q is somewhere between 1 erg and $\frac{1}{4}$ erg. By constructing a large number of equipotential surfaces between P and Q by the rule given above and counting them, we find that the actual work is just $\frac{1}{2}$ erg. Hence the total potential energy equal $2 \times \frac{1}{2}$ erg $=1$ erg.

Since E P $=1$ cm., and the force at P is 1 dyne, E must be, by definition, just one company of electrons.

Hence we have obtained the following important and fundamental result: The total work required to bring up one electrostatic unit (one "company") from infinity to within 1 cm. of another similar and equal unit is 1 erg, and if the distance varies, the total work varies inversely as the distance.

If we increase the repellent body, the work varies as the quantity of electricity, since the effects of two "companies" would be simply added up. But if we double both the repelling and the repelled body, the work is quadrupled. If we keep the repelled body always equal to one unit or company of electrons, we obtain a convenient measure for the potential energy which the repelling body is capable of imparting. The work performed upon one company or unit in bringing it up from infinity to a point P against the repulsive force exercised by E is called the potential function, or shortly the *potential* at P due to E. The following theorems are immediately evident:—

(*a*) All points in an equipotential surface are at the same potential.

(*b*) A charge will always tend to move from a point of higher to a point of lower potential.

(*c*) The force at any point is proportional to the rate of change of potential along the line of force—*i.e.* to the crowding together of the equipotential surfaces.

(*d*) All points on the surface of a conductor are at the same potential. For if they were not, electricity would travel from the higher to the lower potentials until they were levelled up.

We have supposed the repellent body E to be a very small sphere. But it may be a sphere of considerable size without disturbing our calculations, so

long as the electrons or positive atoms are uniformly distributed over the surface. *For then they act outwardly as if they were all concentrated at the centre. We can, therefore, find the potential at the very surface of the sphere. It is $\frac{E}{R}$ where E is the number of units or companies and R the radius* in centimetres. That being so we can calculate the total work required to form the repelled body. Let us build it up unit by unit. To bring the first two companies within R centimetres of each other required $\frac{1}{R}$ dynes. The next unit took double the work, or $\frac{2}{R}$ dynes, the last unit required $\frac{E-1}{R}$ dynes. We get at the sum of these terms by taking the average of the charges during formation. This average is

$$\frac{(E-1)+1}{2}=\frac{E}{2}.$$

The average potential during formation was, therefore, $\frac{E}{2R}$, and since the total number of units to be brought to that potential was E, the total energy consumed in the process was

$$E\times\frac{E}{2R}=\frac{1}{2}\frac{E^2}{R}.$$

Or, if V is the final potential $\frac{E}{R}$, the total energy consumed is $\frac{1}{2}$ E V.

To return to our gramme of pure electricity (p. 24), which we found to produce such alarming results even at the distance of the sun, we can now calculate the energy required to make it.

The gramme, as we have seen, consists of half a trillion ($5{\cdot}6 \times 10^{17}$) companies. This is E. We will suppose these concentrated on a sphere 1 cm. in radius, so that $R = 1$. Then the energy required to build it up is

$$\tfrac{1}{2}\frac{E^2}{R}\text{ ergs} = \tfrac{1}{2}\frac{(5{\cdot}6 \times 10^{17})^2}{1} = 16 \times 10^{34}\text{ ergs},$$

or a billion horse-power working for 680,000 years. The same energy would, of course, be required to build up the same number of charged atoms; but if only 1 gramme of charged atoms is to be built up, the number of companies will be less in proportion to the weight of the atom. Now the atoms are from 1000 to 200,000 times heavier than an electron, and the number of companies per gramme 1000 to 200,000 times less. Hence the energy required to build up a gramme of matter consisting exclusively of positively charged atoms ranges from 16×10^{28} ergs to 4×10^{24} ergs, still an enormous amount.

Since the potential due to a small charged body at a point outside it is simply measured by its charge divided by the distance of the point from its centre, the potential energy, or simply potential of any other charged body placed at that point, will be the product

of its charge by the potential at that point. If the charge on the first body is E_1, and on the second body E_2, and their distance R, the potential is $\frac{E_1 E_2}{R}$. This potential is *mutual*, as it only depends upon their relative position, and it does not matter whether E_1 has been brought up to E_2 or *vice versâ.*

If there are several bodies conferring a potential, the total potential is got by simply adding up the separate potentials, remembering, however, that if the force is attractive instead of repulsive, the potential is negative. The charges will have opposite signs, say E_1 and $-E_2$, and the result $\frac{E_1 \times -E_2}{R}$ is a negative potential—*i.e.* work is gained instead of spent in bringing the charges together.

It follows that if the two charges E_1 and $-E_2$ are equal, the total potential at any point equidistant from them is zero, being in one case $\frac{E}{R}$ and in the other $-\frac{E}{R}$. Now all the points equidistant from two other points are contained in a plane surface normal to the line joining them, and bisecting that line (Fig. 5), it will be noticed that we have here a well-known case of optics. If E_1 is a luminous point and AB a reflecting surface, E_2 will be the "image" of E_1. We might have any other such points on the side of E_1, and if we had equal and opposite charges at the same distance on the other

side, the surface AB would still be an equipotential surface at zero potential. Conversely, if the charges on the other side were taken away, and the surface were kept at zero potential throughout (as a metal plate could be kept at zero potential by connecting it to earth), opposite charges would have to be distributed over the surface, so as to make up for the charges taken away, and keep the force at every point above the surface the same as before. This consideration enables one to calculate the distribution of the electric charge by "influence." The method is a very fruitful and valuable one. It is called the "method of electric images."

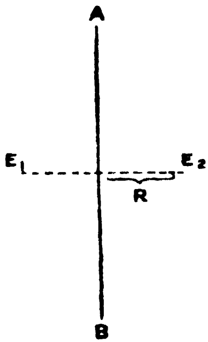

FIG. 5.

Since the surface AB is an equipotential surface, no work is required to move a body along it. If the distance between E_1 and E_2 is 2 R, the distance of the plane from E_1 is R. Now the work required to bring a company of electrons from infinity to within R cm. of the charge E_1 was $\frac{E_1}{R}$ while E_1 was alone in space. This amount has become zero at one point, owing to the presence of E_2. This shows that the potential due to one charge may be counterbalanced and annulled by the potential due to another. Hence, though the potential due to each

body by itself remains precisely the same always, the net potential at any given point depends upon every free charge in the whole of space, and can therefore acquire any value we please. If the point in question happens to be on the surface of a charged conducting sphere, it follows that the "potential of that sphere" is equally subject to the influence of surrounding charges, being lowered by any free charge of the opposite sign. In order to restore its potential to the former high figure we must increase the charge on it. If the potential has been halved, we must double the charge, in order to restore the potential. If the potential is very low, the conductor can carry a great charge; it has, so to speak, a great carrying capacity. This conception of capacity is a very important one, so we must define it more precisely: "The capacity of a conductor is the charge required to raise it to unit potential."

A sphere of radius 1 cm. has unit potential (1 dyne per unit charge repelled) when it contains unit charge (1 "company"). If its radius is 2 cm. its potential is $\frac{1}{2}$, and to bring it to the same potential its charge must be made 2 companies; if 3 cm., 3 companies, and so on. Hence we have the general rule: *The capacity of a sphere is proportional to its radius.*

If the charged sphere has an elastic surface, the mutual repulsion of the charges will tend to bring about an extension of the surface. This may be

proved by blowing a soap-bubble, and then charging it. The bubble expands, and its capacity increases.

When two oppositely charged conductors approach each other, the potential of each is lowered and the capacity increased. Here again the spontaneous motion leads to an increase of capacity.

When two similarly charged bodies repel each other and move apart, their potential is lowered, and, again, their capacity increased.

This is a general rule: *If charged conductors are free to move, they always move so as to make their potential a minimum, and their capacity a maximum.*

The motion thus engendered leads, of course, to a diminution of potential energy. By the law of the conservation of energy, there can be no loss of total energy, so what is lost in potential energy is gained in energy of motion or kinetic energy. We shall have to consider this kinetic energy later on when dealing with the electron in motion.

5. *Condensers.*—We have learnt that when a positively charged conductor is brought near a negatively charged one, the capacity of each conductor is increased.

To simplify matters, consider an infinite plane conducting surface, AB (Fig. 6), and a point, P, outside it. Let the electrons be uniformly distributed over the surface out into infinite space,

and let P contain one company of electrons; then we can prove that the repulsion between the plane and P is independent of the distance of P from the plane, as follows:—

Draw PD, PE, two lines equally inclined to the plane. Draw similar lines all round P, so as to make a cone with P for its apex. The base of the cone will be a circle in the plane surface AB, and all the electrons in that circle will repel P. Let their total repulsion be 1000 dynes. Now remove P to twice the distance, keeping the angles between the lines and the plane the same as before. The lines forming the sides of the cone will be double their previous length, and the base four times its previous area. There will therefore be four times the number of electrons to exert their repulsive force; but since their distance is twice what it was, we must divide the force by 4 (the square of the distance), and the net force will be *the same as before.* The argument will hold good whatever the size of the angle at the apex, and hence we may make it so large, and the cone so flat, that

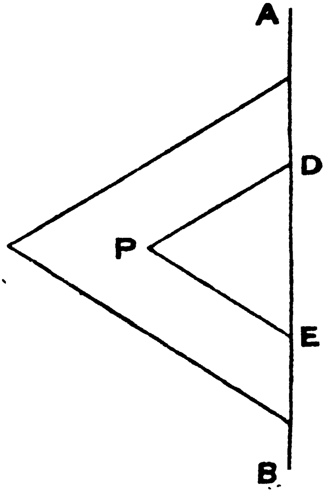

FIG. 6.

the repulsion of the electrons outside the cone is practically imperceptible.[1]

Having thus seen that the repulsion is the same at any distance, let us calculate its amount. Let the point P be 100 cm. from the plane, and let the plane contain 1000 companies on every sq. cm. Then the repulsion between the nearest square cm., *ab*, of the plane will be (p. 38)—

$$\frac{1 \times 1000}{100^2} = \frac{1}{10} \text{ dyne.}$$

Now describe round P a sphere which just touches the plane. Take another square cm. in the surface, say, *cd*. Then, if there were 1000 companies on *cd* they would repel P with the same force as before —viz. 0·1 dyne. But this force would not be so effective as before, since it is inclined to the vertical. Now produce P*c* and P*d* to P*c*[1] and P*d*[1], and let P*c*[1] be $=2$ P*c*. Then if the imaginary surface *c*[1]*d*[1] had the same surface density as *cd* its force on P would be the same, since its charge would be four times and its distance doubled. In producing P*d*[1] to P*e*[1], and completing the intersections with the plane, we mark

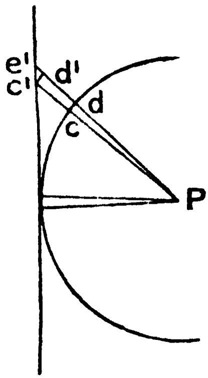

FIG. 7.

[1] We must add that for the above reasoning to hold good the density of the electrons on the surface must be very great; otherwise the redistribution of the electrons, owing to the repulsion of

out a new surface, c^1e^1, whose size is the greater the more Pc^1 slants to the surface. This slant compensates the slant of the push of the repelling electrons on c^1e^1, and we find that their force is 0·1 dyne also, as before. The same argument would hold good for any square cm. we choose to cut out of the hemisphere turned towards the plane. Hence the total push is as many times 0·1 dyne as there are square centimetres on the surface of the hemisphere, viz.—

$$2\pi a\ (\text{radius})^2,$$

or, since the radius is 100 cm., the total force is

$$2\pi \times 0{\cdot}1 \times 100^2 \text{ dynes}$$
$$= 2\pi \times 1000 \text{ dynes},$$

or 2π times (6·2832 times) the number of companies on each square cm. of the plane.

The companies or units per square cm. are called the "surface density of electricity," and are denoted by σ. Hence we have—

$$\text{Force on 1 unit} = 2\pi\sigma$$

at any distance from an infinite charged plane on either side.

In passing through the plane only the direction of the force changes, and not its amount.

P, would produce the same effect as a charge of a company of positive atoms placed at the "image" of P in the plane. This image would attract P, and so lessen the repulsion. If, however, the surface density is great, this attraction may be left out of account, as it has no perceptible influence.

Now let there be two infinite parallel conducting planes at a distance, D, from each other (Fig. 8), and let them have equal surface densities of opposite sign, so that if AB contains, say, 1000 companies of electrons per square centimetre, A^1B^1 contains 1000 companies of positively charged atoms per square centimetre.

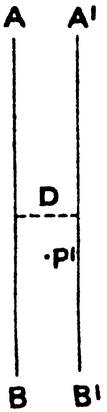

FIG. 8.

Then we can prove that there is no electric force in the field except in the space between the two planes. At a point P^1, for instance, the force due to AB is $2\pi\sigma$, and the force due to A^1B^1 is $-2\pi\sigma$, and the sum of the two forces is zero. In other words, the positive charge on A^1B^1 "neutralises" the negative charge on AB for all infinite space outside the two surfaces.

What is the difference of potential between AB and A^1B^1? In other words, what work will have to be spent on a company of electrons to bring it from A^1B^1 to AB?

It will obviously be the product of the force into D.

Now the force on a company of electrons is a repulsion by AB amounting to $2\pi\sigma$, and an attraction by A^1B^1 to the same amount. These two forces being in the same direction, they add up, and the total force at any point between the planes is $4\pi\sigma$. Hence the work on one company is $4\pi\sigma D$, and that is the difference of potential between AB and AB^1.

A system like the above, consisting of two conductors separated by a non-conductor, is called a "condenser." The most familiar example of a condenser is the Leyden jar (Fig. 9), in which the conductors are made of tinfoil stuck on the outside and inside of a glass jar, and the non-conductor is the glass.

FIG. 9.

The capacity of a condenser is measured by the charge which must be imparted to either conductor to make the difference of potential between them one unit, so that one erg of work must be spent to take a company of electrons from one conductor to another. Since the difference of potential between the two planes is

$$4\pi\sigma D$$

and this is $=1$, we have

$$\sigma = \frac{1}{4\pi D}$$

for the capacity per unit area of the condenser consisting of two infinite planes. This increases inversely as D, so that if we make D small enough, and the plates close together, we can get a condenser of any capacity we please.

The advantage of condensers of large capacity is that we can store up great charges in them with little work, and with little tendency to wasteful discharge, as there is no force outside the coatings. Hence the name "condenser."

If, however, the plates are connected by a wire or other conductor, the mutual repulsion of the electrons towards each other and the positive atoms towards each other will force both into the wire, where they will meet, and electrons will be absorbed by the positive atoms to form neutral atoms. Their potential energy will be liberated and pass first into the form of motion, and then into heat. If the wire is interrupted by a short gap of air, this discharge will break through the air and produce a spark—the well-known spark from the knob of a Leyden jar.

The condenser consisting of two infinite planes is, of course, incapable of practical realisation, and is only introduced for theoretical purposes. It enables us, however, to pass to practical constructions without sacrificing our results of calculation. If the plates were, say, 1 metre square each, the capacity of the condenser would be

$$\frac{100^2}{4 \pi D}$$

approximately; but the distribution of the charges over the plates would not be uniform, as they would be crowded towards the edges. On the other hand, the charges on the central portions would be practically uniform, and if we could separate out a single square centimetre at the centre of each plate, we should approach very closely to the theoretical perfection of our infinite planes, and could safely apply

our formulæ. If we make a clean cut round the small area, but connect it by a fine wire with the larger area, so as to keep it at the same potential as the larger area, we may regard the two small areas as forming an ideal parallel-plate condenser amenable to calculation.

Thus, if their areas are 1 sq. cm., and their charges 1000 companies, and they are 1 mm. apart, the capacity of the small condenser is

$$\frac{1}{4\pi \times 0{\cdot}1} = \frac{1}{12{\cdot}6 \times 0{\cdot}1} = 0{\cdot}795.$$

The charge being 1000 companies, the difference of potential is

$$\frac{1000}{0{\cdot}795} = 1260,$$

so that it will require 1260 ergs of work to bring a company of electrons from the positive to the negative surface.

The attraction between the two areas is

$$\frac{1000 \times 1000}{(0{\cdot}1)^2} = 100 \text{ million dynes,}$$

or nearly 100 times the pressure of the atmosphere upon them. If the distance were 1 cm., the attraction would just about balance the atmospheric pressure, so that if there were a vacuum outside both planes, the atmospheric pressure between them would not push them apart.

If we attached a spring to one of the small plates, and stretched the spring till it pulled the

small plate back into line with the larger plate, we should find that the force on the spring would have to be 102 kilogrammes, or 221 lb. If the charge on each plate were double, the force would be quadrupled, and would become 884 lb. Conversely, if we know the force, we can calculate the number of companies on each surface.

The rule is: "Multiply the distance between the plates by the square root of the force in dynes." The result is the number of companies on each plate. If the force is measured in grammes, multiply by 981 to convert it into dynes.

The number of companies per unit area is found by dividing the number found by the area of the plate (in the above case, by ·1). The above principle is the principle on which the most accurate measurements of electric quantity are made. An instrument, called the Attracted-Disc Electrometer, has been constructed by Lord Kelvin for the purpose. The inventor calls the larger surrounding surface the "guard-ring."

But a more widely used instrument is the Quadrant Electrometer, in which a charged flat needle moves in four quadrants of a circle, two of which are kept at the potential to be measured. The calculation of the working of this instrument is more complicated.

If two parallel planes are bent up into two concentric spheres, it is evident that there will be

nothing to disturb the even distribution of their charges, and their capacity per unit area will be $\frac{1}{4\pi D}$ as before. Hence, if their average radius is r, and D is small, the surface of both spheres will be very nearly $4\pi r^2$, and their total capacity will be

$$\frac{4\pi r^2}{4\pi D} = \frac{r^2}{D},$$

so that, in order to store a large amount of electricity, we must make both spheres large, and their radii nearly equal. If σ is the surface density, the force between the surfaces will be $4\pi\sigma$ per unit area, as in the case of the infinite planes. Now this force is *equal to that due to the inner sphere alone.* For the total charge on the inner sphere is $\sigma \times$ surface $=$ $\sigma \times 4\pi r^2$. This acts outwardly as if concentrated at the centre, so its force at a distance r is

$$\frac{4\pi\sigma r^2}{r^2} = 4\pi\sigma.$$

Hence the charge on the outer sphere exerts no force inside it. The electrons on each element of its surface exert their forces just as usual, in accordance with the inverse-square law; but for every group on one side there is another group, more distant but correspondingly larger, on the opposite side of the same surface, which counterbalances its force. By an argument similar to that used in the case of an infinite plane, we can extend this rule to charged conductors of any shape, and for-

mulate the general rule: "The distribution of charges on a closed conducting surface is always such that the field of force resulting from its own charges, or from forces outside it, is zero at any point within the enclosure."

A conducting enclosure, even a close-meshed wire cage, acts, therefore, as a perfect screen against external electric forces. Such a cage is often used to protect delicate measuring instruments against disturbance from outside. The enclosure can be charged so highly that sparks and brush discharges burst forth at every corner; but the most delicate indicator will fail to discover the slightest effect inside. Any charge that is to exert an effect must be brought inside the enclosure.

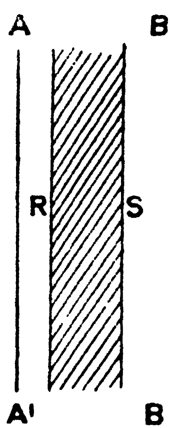

FIG. 10.

6. *Specific Inductive Capacity.*—Let us return to the two infinite planes, and study the effect of introducing between them a conducting plate, RS, filling up half the space between them (Fig. 10). In a conducting substance there are always a large number of electrons and positive atoms ready to obey electric forces. The electrons will crowd towards S, and the positive atoms towards R, until the electric force inside the plate has become zero. To bring this about, the surface density on R must

be equal and opposite to that on AA^1, and the surface density on S equal and opposite to that on BB^1. This gives us, then, practically two condensers, connected in what is called the "cascade" arrangement, the potentials falling like the levels in two successive waterfalls.

What difference will this make in the work required to take a company of electrons from BB^1 to AA^1? The force from S to R is zero. The force from BB^1 to S and from R to AA^1 is the same as before, being due to the same surface density, and, as we have seen, independent of the distance. But the distance over which the company will struggle against this force has been halved by interposing the conductor of thickness $\frac{D}{2}$. Hence the work is halved, and, therefore, also the difference of potential, and the capacity doubled. The same effect would be produced by simply reducing the distance D to $\frac{D}{2}$, without introducing the plate.

We see, therefore, that a conductor introduced between two coatings of a condenser increases its capacity. If, instead of a plate, a multitude of small conductors were introduced, their effect would depend upon their density and size, but it would have the effect of increasing the capacity of the condenser.

The quality whereby a substance introduced between the coatings of a condenser increases its

capacity is called the inductive capacity of the substance, and its *specific inductive capacity* is measured by the ratio by which the capacity of the condenser is increased on substituting the substance for air between the coatings.

The specific inductive capacity of a medium, discovered and named by Faraday, is now usually called its dielectric constant.

Here are a few values: Glass, 3 to 7; ebonite, 2 to 3·5; mica, 7 to 10; petroleum, 2; alcohol, 25; ice, 78; metals; infinite. Condensers are now usually made of mica, on account of its high dielectric constant.

The specific inductive capacity of a medium is due to the number of electrons it contains, and to the extent to which these electrons are displaced out of their normal positions under the influence of an external electric force. In many media, notably guttapercha, this displacement takes some time to disappear after discharge, while in mica there is very little of this remanent electrification.

The electron theory is as yet unable to state what is the configuration or mobility of electrons which produce the various inductive capacities of media. It is known, however, from Maxwell's electromagnetic theory of light, that the dielectric constant is proportional to the square of the time required by long waves of electric force to traverse the medium.

If two charges are separated, not by a vacuum, nor

by air (whose dielectric constant is very little higher than that of a vacuum), but by a medium of dielectric constant, K, the force between them will be, not $\frac{E_1E_2}{r^2}$ but $\frac{E_1E_2}{Kr^2}$. This should be remembered when the charged bodies are immersed in a medium other than air. In the same way, the potential of a charged sphere of radius, R, becomes $\frac{E}{KR}$, and its energy is reduced K times.

7. *Electrostatic Machines.*—An electrostatic machine is a machine used for the mechanical separation of electrons from positive atoms. The earliest machine of the kind consisted of a piece of amber and a woollen cloth wherewith to rub it. This was improved upon by Otto von Guericke in 1663, who made a machine of a sphere of sulphur, which was rotated on its axis while the hand rubbed against it. The sulphur withdrew electrons from the hand, and thus became negatively electrified.

This process is termed "electrification by friction," and was, for centuries, the only known way of producing an electric charge. A glass rod rubbed with silk is the most usual frictional apparatus for experiments on a small scale. In this case, the silk withdraws electrons from the glass, leaving the latter "positively" charged.

The process whereby bodies become electrified by friction is still very obscure. It is known that it

depends largely upon the condition of the surface, and the chemical nature and structure of the bodies.

Of commonly known bodies, a catskin gives up electrons most easily, and sulphur absorbs them most easily, so that a machine made of those two substances is very effective.

We may suppose that there are at the surface of every uncharged body a number of electrons ready to part company with the positive atoms to which they are attached. A catskin would be particularly rich in those loose electrons, and sulphur particularly poor. The effect of rubbing the two together is to give the loose electrons an opportunity to pass from the skin to the sulphur, where they are more strongly held. Once we have a charged body, it is easy to obtain other charged bodies by influence. We have seen above (p. 37) that if a conductor is brought near a negatively charged body—say, a block of rubbed sulphur—the free electrons are pushed to the end farthest from the sulphur and the positive atoms are attracted towards it. If we break the conductor in two, and take away the sulphur, we obtain a negatively charged conductor and a positively charged conductor. Or, instead of breaking the conductor in two, we may make it up of two conductors in metallic contact, and separate them while still in the vicinity of the sulphur. Or we may let the repelled electrons pass into the earth, and then break the connection and obtain a positively charged

conductor only, and this process may be repeated indefinitely, so that we can manufacture any number of positive atoms from a single charge of electrons, though not without setting free an equal number of electrons.

The earliest electrostatic machines separated electrons and positive atoms by friction, and then used their mutual attraction for storing them in condensers. This storage is closely akin to the storage of water in vessels, cisterns, and reservoirs, where it is held by the attraction of the earth. Only the substances used are adapted to very different requirements. For water, air is pervious and metal impervious. Hence the water is surrounded by metal or other solids on the side nearest the earth. For electricity, on the other hand, air is impervious and metal pervious. Hence the charged metal must be "insulated" by means of some non-conductor.

The more modern machines work by influence, and are more efficient, but their efficiency is still far from perfect. The ideal electrostatic machine is one in which electrons can be separated from positive atoms with an expenditure of work which can be entirely recovered on allowing the two electricities to recombine.

A limit is set to the amount of electricity separated and stored in condensers by the "dielectric strength" of the medium. When the air or other dielectric

between the coatings of a condenser is subject to a certain limiting stress, an electron breaks out from the negative coating and rushes across towards the positive coating. In doing so it collides with a number of neutral atoms, and breaks them up into "ions" of opposite signs. These ions practically reduce the distance between the coatings, and thereby increase the stress. This, again, leads to a rush of further electrons and positive atoms towards each other, and we have a whirl and turmoil of movements, collisions, separations, and recombinations. We have, in fact, an electric spark; or if it takes place on a large scale in the atmosphere, we have lightning and thunder.

CHAPTER IV

THE ELECTRIC DISCHARGE

1. *Discharge in General.*—Whenever an electron moves from one space into another, it may be said to produce a discharge from the first space into the second. But an "electric discharge" is usually understood to mean the process whereby a body loses the charge that marks it off, electrically speaking, from its surroundings.

These "surroundings," such as tables, walls, &c., are usually connected with the earth by more or less good conductors, and bodies cease to exhibit an electric charge when they are at the same potential as the earth.

Now what is the potential of the earth? In other words, what is the work required to bring a company of electrons from infinity to the surface of the earth? The question is not easily answered, but the work may perhaps be roughly estimated at a million ergs. For the charge of the earth is negative. It repels electrons, and attracts positive atoms. It behaves in that respect like an electron, and who knows but that if an electron were magnified to the size of the earth it might show a marked resemblance to our own

planet? The resemblance is increased by the fact that the sun has a large positive charge, estimated by Arrhenius at 25×10^{19} "coulombs" ($= 7{\cdot}5 \times 10^{20}$ companies), which gives it a potential of 10^{10} units or 3 billion "volts." The sun thus resembles a positive atom with a number of negatively charged electrons in the shape of planets revolving round it. But the analogy fails when we measure the forces between the sun and planets. For the electric attraction is found to be quite imperceptibly small in comparison with the gravitational attraction, and astronomers may safely leave it out of their calculations.

Even if the negative potential of the earth is a million units (300 million "volts") as supposed, its action upon an electrified body near its surface will be excessively small. If this potential were solely due to the earth's own charge, that charge would be 6×10^{14} companies, and this may be supposed to be concentrated at the centre—*i.e.* at a distance below us of 6×10^{8} cm. Consequently the repulsion exerted upon one company of electrons at the surface will be

$$\frac{6 \times 10^{14}}{(6 \times 10^{8})^2} = \frac{1}{6} \times 10^{-2} \text{ dynes},$$

or about $\frac{1}{500}$th of the normal weight of a milligramme.

This quantity is beyond the limit of sensibility of our most delicate balances.

There is, however, a constant streaming of electricity up and down through the air, which is greatly influenced by the weather, and gives rise to the

phenomena of thunderstorms and atmospheric electricity in general. Outside the atmosphere the earth behaves as a highly charged body, and discharges of its negative electricity become occasionally visible about the poles in the shape of the Aurora.[1] The conductivity of the air, like that of any other body, depends solely upon the density and mobility of the ions or charged bodies contained in it. These ions may be single electrons or positive atoms, or they may be these associated with more or less neutral matter. The presence of these ions in the air constitutes the "ionisation" of the atmosphere. There can be no discharge without ionisation.

This is a fact which has only recently come to light. It has been known for a long time that every charged body exposed to the air is gradually discharged. But that was attributed to moisture or particles of dust, or even to the charging of air molecules. We know now that the discharge takes place when both moisture and dust particles are rigidly excluded, but does not take place if ionisation is prevented. If there is ionisation, the amount of such ionisation determines the rate at which the body is discharged.

Now ions may be contained in solids, liquids, or gases, and discharge may therefore take place through any of these, or even through a vacuum. But in the case of a vacuum, the ions have to be provided by

[1] *See* P. Villard, *Comptes Rendus*, July 9, 1906.

the discharging body itself, since the vacuum is otherwise a perfect insulator. In other cases, too, the discharge has to furnish the ions as it goes along. This is notably the case in the electric arc lamp and the spark discharge, where the air is too poor in ions to convey the whole discharge. But before such a discharge can be inaugurated, it is necessary, as a rule, that a few ions should exist in the medium through which the discharge is to take place. If no such ions exist, the medium is a perfect insulator. A discharge can only be made to pass through by means of a great force sufficient to project ions from the charged bodies, and mechanically break down the insulator.

All these various forms of discharge may be classified under five heads, accordingly as they take place through insulators, gases, solid conductors, liquid conductors, or a vacuum.

2. *Discharge through Insulators.*—Insulators are substances which contain no roaming electrons. Their electrons are firmly bound up with atoms, and the latter again are usually bound up together in complex molecules. The substances are therefore, as a rule, chemically inactive: they do not oxidise, and they do not dissolve in water. Paraffin, a typical and valuable insulator, is named from its lack of chemical action (*parum affinitatis*). And chemical affinity, in all probability, is a matter of detachable electrons and nothing else.

When the electrons of a substance are not detachable from their atoms or molecular groups, they cannot easily be made to enter a metal to neutralise the positive atoms which that metal may contain. And, on the other hand, the positive atoms being amply provided with electrons, are not prone to combine with electrons from outside.

Many of the best insulators, like paraffin, beeswax, guttapercha, ebonite, and amber, are highly complicated carbon compounds. They have no great density; their molecules are not closely packed, and their atoms are not heavy. The complex molecular aggregations are well separated from each other, and the electrons are effectively imprisoned in them.

If an insulator like benzene, C_6H_6, is bounded on one side by a surface containing a large number of free electrons, and on the other side by a surface containing a large number of free positive atoms, the electrons in the benzene molecules will be wrenched to a greater or less extent out of their position and pulled towards the positive atoms; whereas the carbon and hydrogen atoms, and more especially the latter, will be pulled towards the surface containing the excess of electrons. If there were any roaming electrons in the insulator they would find their way out, and would neutralise the positive atoms wherever they encountered them, thus producing a discharge. But a good insulator being a substance which contains no such roaming electrons, no discharge will take

place unless the force is strong enough to pull the electrons out of the benzene molecules and set them a-roaming. When that happens, events will begin to march rapidly: electrons will fly towards the positive terminal. They will be as quickly replaced by others from the negative terminal surface. These double combinations will give rise to a considerable commotion, which will break up further molecules and impart a conductivity to the insulator by providing it with free electrons and free positive ions. In the direct line joining the terminals a rapid separation and recombination of ions will occur, and will go on at an increasing rate as the conductivity of the insulator increases. The heat produced will volatilise the liquid insulator, and through the ionised gas the discharge will pass like an avalanche, the ions acquiring a velocity growing with the free path along which they travel under the impulse of the electric force. Even when that force is spent, the ions will continue to fly on, like a pendulum swinging up against gravity, and like it, they will return, producing a momentary current in the opposite direction. This may be followed by several minor oscillations, until at last the energy is all radiated away into space, and equilibrium is re-established.

Such is the process which we witness in the electric spark, or, on a larger scale, in the lightning-flash. If the insulator is a solid, the path of the

discharge is marked by a perforation. Glass, mica, ebonite, cardboard may be pierced in this manner.

It takes some 30,000 volts (100 electrostatic units of potential) to pierce a thickness of 1 mm. of the best insulators. This means that the work done in passing from the negative to the positive terminal by one company of electrons is 100 ergs. This energy is sufficient to produce the necessary number of ions to keep a further discharge going.

If the thickness of the insulator is greater, the difference of potential required is also greater, but not in the same proportion. If D is the thickness of dielectric, the necessary difference of potential increases as $\sqrt[3]{D^2}$ so long as the distance does not exceed a few centimetres. It requires 58,000 volts to pierce a plate of mica (a complex silicate of aluminium and other metals). This great insulating power is due not only to the complexity of the molecules, but to their segregation in numerous successive strata.

3. *Discharge through Gases.*—When a positively charged conductor is placed near a negatively charged conductor in air, the opposite charges crowd towards the surface facing the other conductor. The air produces no effect beyond slightly reducing the effective distance between the conductors, which it does by the displacement of the charges constituting its neutral atoms, the electrons straining towards the positive conductor, and the positive atoms straining

towards the negative conductor. The superfluous electrons in the metal are so much entangled with the molecular aggregates of the metal that even their mutual repulsion and the attraction of the opposite charges in the positive terminal fail to send them out into the open air. And the same state of things obtains among the superfluous positive atoms in the positive terminal, except that they are held even more firmly than the electrons. For actual expulsion, some strong agency is necessary. Radioactive substances like radium and uranium are in such a state of unstable equilibrium that an atomic catastrophe every now and then sends an electron or positive atom flying out into space. But ordinary substances require either a high temperature or ultra-violet light, or the impact of ions, to enable their own ions to escape. It is only under exceptional conditions that the mere pressure of similar charges suffices to project some of them outside the conductor.

When, however, the air is ionised, *i.e.* filled with particles each linked with an electron or positive atom, these ions beat against the terminal opposed to them in sign, and shake or pull the opposite charge out of the metal.

There are a number of ways of ionising air. It can be done by simply heating it or illuminating it with ultra-violet light, or transmitting Röntgen rays or Becquerel rays through it. The energy thus

supplied is converted into the potential energy of ionisation. But since the ions are constantly recombining, the ionisation must be kept up artificially.

When this is done an electric discharge can take place through air, just as through a metallic conductor—a silent and steady and invisible discharge. The only difference is that the fall of potential is not uniformly distributed, being more rapid near the terminals, where ions of the opposite sign congregate. Such a discharge is called a "dependent discharge," depending as it does upon a constant supply of external energy for ionisation.

When, on the other hand, the discharge furnishes its own ions as it goes along, we have an "independent discharge." This is done in a variety of ways. The most familiar example is the electric arc lamp, where the carbon terminals give off vapour of carbon, and furnish the ultra-violet light necessary for its ionisation.

Another familiar example, and the oldest known, is the electric spark, and its great natural counterpart, the lightning-flash. Both these are almost invariably intermittent, lightning being a quick succession of flashes in the same direction, often preceded by a feeble pilot discharge which passes from one stray ion to another, just as it finds them, and thus marks out a forked path for the main discharge to traverse.

The forms of discharge which allow the greatest

insight into the actual processes going on are the point, brush, and glow discharges, chiefly in rarefied gases.

A point discharge between a metallic point and a plate is the simplest form of gas-discharge known. Let a sharp point, P, be placed opposite a circular plate, AB, in air (Fig. 11). Let the point be kept at a negative potential, and AB at a positive potential. Then when the difference of potential is sufficient, say a few hundred volts, a glowing steady spark is seen at the point. This spark really consists of two luminous strata separated by a narrow dark space.

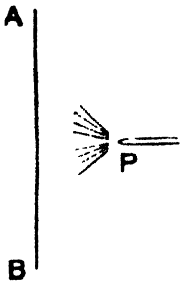

FIG. 11.

A few stray positive atoms are required to start the discharge. They are attracted to the point, near which they find an intense and concentrated electric force. Their motion towards the point is constantly accelerated, and when they get close up to it, it is sufficiently rapid to split up the gaseous molecules into ions. This splitting up is facilitated by the presence of the metal, which appears to exert what chemists call a "catalytic" action. The region where this splitting up takes place is the luminous layer immediately adjoining the point. The electrons liberated by the ionisation are repelled by the point, and fly out into the gas. They also are accelerated until they re-

quire sufficient energy to ionise the gas, and *their* field of action is marked by the second luminous stratum. The dark space between, called the "dark cathode space," is the region where both kinds of ions are acquiring energy of motion, but not spending it, and therefore not producing any luminous effects.

This double ionisation also goes on when the point is positively charged, and the plate negatively. Only then the dark space is still smaller. When the difference of potential is very great, the electrons from the negative point fly beyond the region of ionisation and attack the gas further towards the plate, ionising it freely. This beautiful phenomenon is known as the brush discharge. Tesla's flame discharges and the discharges obtained by means of the Wehnelt interruptor, are varieties of it.

The form of discharge showing the greatest variety of phenomena is the glow discharge, as seen in vacuum tubes. It is this form of discharge, indeed, which, after being a great source of perplexity, ultimately was instrumental in elucidating the whole realm of electric discharges. The reduction of the pressure of the gas allows freer play to the ions. It gives them a greater "free path" along which they can follow the acceleration of the electric field, and thereby acquire kinetic energy. Ionisation is thus facilitated, and conductivity more rapidly acquired.

The slow discharge in a vacuum tube consists normally of five distinct parts—viz. the cathode layer A, the dark cathode space B, the negative glow C, the intermediate space D, and the positive column E (Fig. 12). The three luminous layers (shown dark in the diagram) are those in which ionisation is going on. They are the scenes of conflict and collision, whereas the other spaces are the scenes of free fall along the lines of electric force. At the cathode layer A, positive atoms are

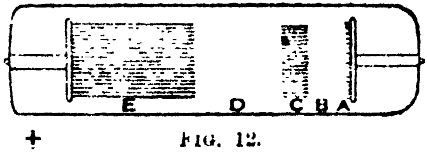

FIG. 12.

ionising the gas next the cathode with the help of the metal. As in the case of the point discharge, the ions thus formed follow the electric force, the positive atoms neutralising the free electrons of the cathode, and the electrons traversing the dark cathode space to ionise the neutral atoms in the body of the gas at C. There again, both positive atoms and electrons are liberated, and the latter move still farther towards the anode, producing further ionisation when they have acquired sufficient velocity, and then we get the positive column E. Sometimes it happens that all the electrons proceeding from C have nearly the same velocity.

They then reach ionising speed within nearly the same distance, and are stopped at the beginning of the positive column. Before they can acquire further ionising power, they must traverse another dark space, and so on alternately, the final result being the "stratified" positive column, which forms such a striking display when the tube is long enough. If the tube is shortened, the positive column is gradually "swallowed" by the anode until the discharge resembles the ordinary point discharge.

The above is a general outline of the main phenomena in gaseous discharges. But they exhibit an almost infinite variety, and still offer a fruitful field of investigation. When the exhaustion of the vacuum tube is carried to a very high point, the phenomena become of profound interest to the electron theory. For the electrons projected from the cathode play a very prominent, and eventually an almost exclusive, part. They proceed in straight lines from the cathode, like rays of light, and are therefore commonly called "cathode rays." It was Crookes who first pronounced them to be a kind of matter ("radiant matter"), and we now know that they consist of particles about 200,000 times smaller than the ordinary atoms—viz. the electrons themselves. But the positive atoms also take the appearance of rays. When the cathode is perforated, such rays are seen to emerge from the

back of it. They have been called "canal rays," but they simply consist of positively charged atoms, or atoms or molecular aggregates deprived of electrons.

A noteworthy fact with regard to gas discharges is that the amount of electricity passing (the "current") is not necessarily proportional to the difference of potential between the electrodes. It depends upon the ionisation, and that is influenced and enhanced by the passage of the discharge itself, owing to collision between the ions. In the dependent discharge, again, where the ionisation is provided by an external agent, the current can never exceed a certain value, fixed by the number of ions supplied. When these are all engaged in conveying the current, a change in the potential fails to change the current. There exists, in fact, a "saturation current." This, as we shall see, is not the case in metals.

Discharge through flames is a special form of gaseous discharge, and depends upon the natural ionisation produced by a high temperature. Heat also exerts an action upon the discharge from metals. It is found that a hot platinum wire is discharged more readily than a cold one. A negatively charged platinum wire is easiest discharged when surrounded by hydrogen; that being a gas whose atoms lose their electrons easily. They surround the negative wire and pull out its elec-

trons. When a hot platinum cylinder is charged positively and hydrogen is made to diffuse out from it, the hydrogen atoms, with their positive charges, rapidly free the cylinder from its positive charge by conveying it into the surrounding space.

4. *Discharge through Solid Conductors.*—In gases at ordinary pressure, or in a partial vacuum, we have to do with molecules possessing a certain free path, which, though very small (about $\frac{1}{100000}$ cm.), yet gives them some little interval of undisturbed motion.

In metals, on the other hand, the atoms are packed close together. How closely may be found by a simple calculation as follows. The mass of a copper atom is 70×10^{24} grammes. A cubic centimetre of copper weighs 8·9 grammes. That cubic centimetre therefore contains $0{\cdot}127 \times 10^{24}$ atoms of copper, and each atom will have a volume of $7{\cdot}9 \times 10^{-24}$ cc. to tself. If this volume is a small cube, its side will be 2×10^{-8} cm. This length is just the diameter of a molecule of hydrogen, so that if we fill up the small cubes with molecules of hydrogen, they will just fit tight. How, then, will the copper atoms fit? We do not know the exact size of the atoms of copper, but can make a very close guess. We may take it that the diameter of a molecule of copper is not more than twice the diameter of a molecule of hydrogen, since we know that the mercury molecule is not more than 1·7 times as thick. Therefore the

copper atom is just about the size of the hydrogen molecule, and fits equally tight in the small cube.

The copper atoms are therefore about as closely packed as they will go. Hence copper cannot be perceptibly compressed. But it also explains why the loose electrons attached to the copper atoms are practically free to obey outside electric forces. For they easily get into the neutral zone between neighbouring positive atoms, and are then under the influence of the outside force only. This happens, according to J. J. Thomson, about 40 million times per second to each electron. (In bismuth, at all events.) As a consequence, the whole of the loose electrons in a metal (I mean those electrons which can enter or leave the atom without producing a charge sufficient to stop the process) are every now and then set free to obey external electric forces. *Their motion under the influence of those forces constitutes metallic conduction.* From this simple fact the most important laws of metallic conduction may be immediately deduced.

Schuster[1] has estimated that a metal contains from one to three mobile electrons for each atom. Copper contains about three mobile electrons for every two atoms. We must therefore imagine these electrons darting in and out among the atoms, and ready to obey the pull of an electric force whenever they happen to be free, which happens millions of

[1] A. Schuster, *Phil. Magazine*, Feb. 1904.

times per second. The path of freedom increases as the metal cools and the atoms arrange themselves in larger aggregations. Hence the electrons in cold metals follow the electric force more readily than in hot metals.

Now it may be asked whether the atoms themselves do not also obey electric forces. The answer is that they do so when they are linked to either more or less electrons than they contain in the neutral state. If linked to more electrons, they have a negative charge; if to less, they have a positive charge. In the former case they tend to go the same way as the electrons, while in the latter case they tend to move in the opposite direction. But, being about a hundred thousand times more bulky than the electrons, they make little headway, and, except in extreme cases, their motion may be neglected, and we may take it that the electrons alone obey the pull of the electric force—*i.e.* that it is they alone who form the "electric current" in metals. But it is evident that they move from the negative to the positive side, and, therefore, in the direction opposite to that in which an "electric current" has hitherto been supposed to flow. This fact constitutes a serious difficulty in the present state of transition of electrical terms. We cannot hope that people will at once revise all their electrical terms, and reverse all their previous notions. The textbooks alone would prevent that. It is, therefore, imperative that we should use a term which

cannot possibly mislead any one. For this purpose I propose to use the term "electron current" for the movement of electrons. Whenever I speak of "the current" pure and simple, I shall mean the movement of electric charges without reference to their direction. When the direction from positive to negative is to be understood, I shall speak of the "positive current."

When the current is not conveyed by isolated electrons, but by "ions"—*i.e.* larger aggregates of atoms containing a positive or negative charge—there are two real displacements in opposite directions, as in electrolysis. It will then be expedient to talk of a "positive current," denoting the flow of positively charged matter, and a "negative current," to denote the flow of negatively charged matter. The total current is the sum of the two.

Having settled these important matters of terminology, we may now proceed to unravel the mysteries of the electron current in metals.

To simplify matters, we will take, as before, two infinite parallel plates, AC, BD, 1 cm. apart, and having a difference of potential such that it takes 1 "erg" of work ($=\frac{1}{13660000}$ foot-pound) to move one company or electrostatic unit of electrons from the positive to the negative plate. This is the electrostatic unit of difference of potential. It can be obtained practically by connecting the two plates with the terminals of a battery of some 300 Daniell cells.

Now let a cube of 1 cm. side, consisting of copper, be inserted between the plates, and touch both of them. What will happen?

Obviously, the two quadrillion mobile electrons contained in the cubic centimetre of copper will be set in motion towards the positive plate. If they could fall freely along the lines of force, they would arrive at the positive plate with a velocity of 10^9 cm. per second, since the comparatively large force of 1 dyne acts through 1 cm. on the insignificant mass of each company of electrons ($1{\cdot}78 \times 10^{-18}$ grammes). Each company which falls through the whole centimetre acquires 1 erg of energy; but as, on the average, the electrons only fall through half that distance,

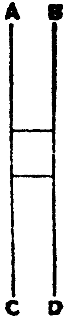

FIG. 13.

we get the energy acquired by the total electrons in the copper in falling on to the positive plate by multiplying the number of companies by half an erg. This number of companies is $6{\cdot}5 \times 10^{14}$, so that the energy acquired by them in falling on to the positive plate is 325 billion ergs—a quantity sufficient to evaporate several hundred pounds of water. Since this process would only take $1{\cdot}9 \times 10^{-9}$ of a second, and a further supply of electrons from the negative plate would be ready to repeat it, it may be realised what an enormous evolution of energy would be going on between the plates if the free path of each electron were 1 cm.,

in other words, if the conductivity of the copper were practically infinite.

But, as a matter of fact, that is not the case. There are two factors which hinder a free discharge. In the first place, the electrons are every now and then encountering the closely packed neutral copper atoms, and colliding with them. When an electron is suddenly stopped like that, it cannot rebound without loss of energy, as a perfectly elastic or a perfectly hard ball would from another. As we shall see later on, the acceleration or retardation of electrons is attended by radiation, and radiation means loss of energy. A well-known example of such radiation are the Röntgen rays, which are wave-pulses sent out into the ether when a cathode particle, *alias* an electron, strikes an obstacle.

Considering how closely the atoms are packed, we may take it that an electron loses nearly the whole of its energy by radiation whenever it collides with a neutral atom. If it has any to spare, it will revolve round the atom and radiate out its spare energy in doing so.

Another factor which hinders the free discharge of electrons is this binding together of a positive atom and an electron until a collision sets it free. It has been estimated that for every 5000 electrons thus temporarily bound, there is only one electron free to roam at any given instant of time. We cannot therefore count upon more than $\frac{1}{5000}$th of the

total number of mobile electrons to take part in metallic conduction at any given instant.

We have estimated the total mobile electrons in the cubic centimetre of copper at 1·9 quadrillion. Of these, 380 trillion will therefore be available for conduction at any given time. Since successive copper atoms will be on the average 2×10^{-8} cm. apart, we may suppose that each electron is stopped every time it has gone that distance. What time will it require to cover the one centimetre distance between the plates?

It can be easily shown that the time will be increased in proportion to the square root of the number of stoppages. For by a well-known law of falling bodies

$$t = \sqrt{\frac{2s}{g}}.$$

Thus, if there are four compartments, $s = \frac{1}{4}$, and $t = \frac{1}{2}$, so that the total time is $4 \times \frac{1}{2} = 2$.

Now, there are $0·5 \times 10^8$ such "compartments" in our case, so that the time will be increased.

$$\sqrt{0·5} \times 10^4 \text{ times} = 0·71 \times 10^4 = 7100.$$

The time required for falling free having been $1·9 \times 10^{-9}$ second, the time required by the electron for threading its way through the copper will be

$$7000 \times 1·9 \times 10^{-9} = 1·35 \times 10^{-5} \text{ second.}$$

In that short time the whole of the freely moving

electrons, 380 trillion in number, will have passed out of the copper into the positive plate, and their places will have been taken by reinforcements from the negative plate. In one second no less than

$$\frac{380 \text{ trillion}}{1{\cdot}35 \times 10^{-4}}$$

electrons will pass through any cross-section of the conductor. This is the electron current. It is equal in electric quantity to the ordinary or positive "current," but of opposite sign. In practical measure it comes to about 3,000,000 ampères, a current of such intensity that it would melt and evaporate the copper in a fraction of a second.[1]

The property whereby a conductor absorbs the kinetic energy of the electrons and converts it into heat is called the "resistance" of the conductor.

The current, or current strength, is measured by the number of electrons passing any section of the conductor in unit time.

We might define unit current as the passage of one company of electrons per second across any section of the conductor. But such a current would be exceedingly small, and could hardly be measured by the ordinary instruments. It is usual to measure currents by "ampères," or "coulombs" per second.

[1] The current calculated from the observed resistance is 188 million ampères, so that the electrons are not stopped quite so often as above supposed.

One coulomb consists of 3×10^9 companies, or $8{\cdot}7 \times 10^{18}$ electrons. In accordance with the principle of emphasising the atomic nature of electricity, I shall call the "coulomb" an "army" of electrons (or positive atoms), and we shall know that this army consists of 8·79 trillion men and may be divided into 3000 million companies.

When one army of electrons passes across any section of a conductor in one second, that conductor is conveying unit current, or one "ampère."

The amount of electricity passing every section must obviously be the same. For if more electricity entered by one section than what issued by the other the metal between the two sections would be accumulating electricity, and such accumulation would be rapidly cleared away by the mutual repulsion of the charges.

The amounts of electricity dealt with in metallic conduction are much larger than those we have to do with in electrostatic charges. In these, as we have seen, it is not practicable to have more than one-millionth of the total electricity in the shape of free charges. But within the uncharged metal, every free electron is compensated by a positive atom, and is free to move, although it does not form an electrostatic charge measurable outside.

We will now proceed to consider the current under various circumstances.

Suppose that in the case of the copper cube the

current is reduced 1000 times. That will mean that only one-thousandth of the electrons will reach the positive plate per second. But it will also mean that the average steady velocity of each electron —in fact the rate at which it does its work in overcoming the resistance of the conductor — is reduced in the same proportion. In any element of volume of the conductor, the rate at which energy is converted into heat will be reduced in the proportion of 1 : 1000², or 1 : a million. And in general, the heat evolved per unit volume in unit time *is proportional to the square of the current.* (Joule's Law.)

If, on the other hand, we reduce the difference of potential between the plates to $\frac{1}{1000}$th of its former value, we reduce the force acting upon the electrons in the same proportion, and their steady average velocity and rate of work will be reduced to $\frac{1}{1000}$th. For every thousand electrons which formerly passed a cross-section, only one electron will pass now. The current, therefore, is *proportional to the difference of potential at the ends of the conductor.* (Ohm's Law.)

Now, instead of one copper cube, let there be two. Then, since the plates are supposed to be infinite, and contain a supply of electrons and positive atoms equal to any demand, there will be two equal currents, and the total current will be twice what it was before. Following up this argument, we see that the current

is *proportional to the sectional area of the conductor.*

Next, let the two copper cubes be arranged one behind the other (Fig. 14), so that the current has to traverse both in succession, and let the difference of potential be the same as before. To secure this, we shall have to reduce the surface density of electricity on the plates to one-half, and therefore the force will be halved, and also the steady velocity of the electrons. Hence the current itself will be half its former value, and if we increased the length of conductor n times, we should also reduce the current n times. Therefore the current is *inversely proportional to the length of the conductor*, other circumstances being equal.

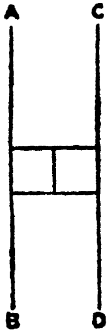

FIG. 14.

If, while keeping the plates the same distance apart we connected them by a slanting conductor (Fig. 15), we should reduce the effective force on the electrons in the same proportion as we increased the length of the conductor, and should, therefore, also reduce the current in the same proportion, so that in this case also the current is inversely proportional to the length of the conductor.

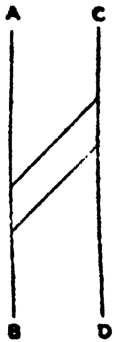

FIG. 15.

The geometrical shape of the conductor is, however, not the only factor which influences the current.

If iron were substituted for a copper rod of the same dimensions, the current would fall to one-sixth its former value. The property whereby one metal conducts electricity better than another is called its (specific) conductivity. Its reciprocal is called its "resistivity," or specific resistance. The actual resistance of a metallic rod of uniform section may be arrived at by multiplying its resistivity by its length and dividing by its sectional area.

The resistance of a body may be measured by the amount of energy transformed into heat by a current of one ampère passing through it for one second. A piece of iron develops six times as much heat as a piece of copper. The resistance of an iron wire 1 cm. long is, therefore, equivalent to that of a copper wire of the same thickness, but 6 cm. long. Therefore, if we have an iron wire and a copper wire, each 1 cm. long, attached end to end, and conduct the current through both, we get the same result as if we passed the current through a copper wire 7 cm. long. In other words, the resistance of two successive conductors is equal to the sum of the resistances of the conductors taken separately, and the current acts accordingly.

We are now in a position to fully formulate Ohm's law. If a difference of potential is maintained at the ends of a conductor, or system of successive conductors, the current through the conductor or the system is proportional to the difference of potential,

and inversely proportional to the resistance between the ends.

Such a law as the above does not, of course, hold good unless the number of carriers of electricity is a constant quantity. In gaseous discharges, as we have seen, ionisation is continually going on, and the current often increases much more rapidly than the difference of potential. In metals the detachable electrons are all available for conduction, although a large proportion of them are temporarily bound up with atoms at any given instant. An increase of the difference of potential does not affect the ionisation in metals, since in them ionisation is final in the natural state.

When a current flows into a branched conductor, the current flowing towards the point of division must be equal to the sum of the currents flowing away from it. For otherwise there would be an accumulation of either electrons or positive atoms at the junction. When any number of conductors meet at the same point, the sum of the currents towards the point is equal to the sum of the currents from the point. This rule is known as Kirchhoff's first law.

The current is seen to behave like an incompressible fluid. As a matter of fact, electricity *is* a fluid, and, indeed, a gas, possessing a pressure of several thousand atmospheres in most metals, and having the same temperature as its surroundings. What

distinguishes it from ordinary gases is the enormous expansive force it possesses apart from its temperature. Ordinary gases, when deprived of all heat, are at the same time deprived of all expansive force But the electric gas, made up of electrons, has an enormous explosive power, even at the absolute zero of temperature. Nor is electricity, regarded as a fluid, really incompressible. It can be compressed to the extent of about a millionth, as is done in charging a conductor with a high negative charge. But that is the utmost limit to which we can push the compression, and in ordinary apparatus that would be inappreciable.

In the imaginary experiments described above, I have said nothing about the manner in which the infinite plates AB and CD may have been charged, because that does not affect the result. But any electrostatic machine capable of supplying the required number of electrons and positive atoms may take the place of the infinite plates. Let such a machine supply the small plate N with sufficient electrons to keep it at a (negative) potential of one volt, and let the machine at the same time withdraw a corresponding number of electrons from M, so as to keep M at the potential of the earth; then

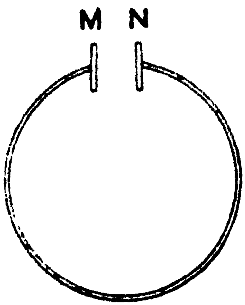

FIG. 16.

the machine will be doing a certain amount of work on the negative electrons to take them from M to N. That work will be one erg *for every "army" or* "coulomb" of electrons; it is called the "electromotive force" (E.M.F.)[1] of the electric machine.

When the work is done without loss between M and N, the E.M.F. is simply the resulting difference of potential between M and N, for it represents the amount of energy that can be obtained per unit of electricity out of the wire in the shape of heat. But when the electric machine works in such a manner that not all its work is transformed into potential energy, but some of it lost in overcoming a resistance, the current is reduced in proportion to this additional resistance, and the extra work is deducted from the difference of potential available at the terminals M and N. The electromotive force of the machine is then no longer equal to the difference of potential between the terminals M and N, but larger.

Ohm's law also covers this case of what is called "internal resistance." For it states that the current is in all cases proportional to the total E.M.F. (whether due to one machine or several in series), and inversely proportional to the total resistance.

An apparatus like the above, consisting of an

[1] The term electromotive *force* is unfortunate. It is not a force, and it is not work, but work per quantity of electricity. Other terms sometimes used, like tension or pressure, are equally unfortunate. We still await a satisfactory word.

electric machine or other electromotive agency and a conductor joining its terminals, is called an "electric circuit." Since electricity can neither be created nor destroyed, there must in the end be a circulation of electricity, and if there is a continuous flow such a flow must ultimately constitute a circuit.

The current in a circuit can, by means of Ohm's law, be calculated in a simple manner. The E.M.F. is measured in volts, each of which is $\frac{1}{300}$ of an electrostatic unit of difference of potential (1 erg per company). The current is measured in ampères, or coulombs per second. Resistance is measured by a unit called the "ohm," which is the resistance of a thread of pure mercury 1 sq. mm. in sectional area and 1063 mm. long. The resistance of any other conductor may be calculated from its dimensions and its resistivity. That being done, we obtain the current by the equation—

$$\text{Current in ampères} = \frac{\text{E.M.F. in volts}}{\text{resistance in ohms}},$$

or

$$C = \frac{E}{R}.$$

5. *Discharge through Liquids—Electrolysis.*—We have now to consider the case where the metallic circuit containing the current-yielding electric machine is broken at one point, and a liquid is interposed in the gap. If the circuit consists of one metal only, and but one liquid is introduced, two things may happen: (*a*) no current passes;

or (*b*) a current passes. The former alternative happens when the liquid is an insulator, like oil. The latter happens when the liquid contains ions.

Pure water contains practically no ions at all, and is therefore a nearly perfect insulator. But it has a remarkably high power of splitting up the molecules of other substances into ions. Thus, if it contains a drop of hydrochloric acid (HCl), it splits up nearly every molecule of the acid into ions; these being atoms of hydrogen and atoms of chlorine respectively. To put it more precisely, if water contains 0·0036 per cent. of hydrochloric acid, then 99 per cent. of all the acid molecules will be split up (or "dissociated" or "ionised") into H and Cl, and the remaining 1 per cent. will be present as HCl. This hypothesis, which is greatly at variance with the old chemical views of the constitution of a dilute acid, is called the "ionic" or "dissociation" hypothesis, and has been elaborated chiefly by the celebrated Swedish physicist Arrhenius. It was this hypothesis which first utilised the conception of an atomic structure of electricity, as suggested by Faraday's laws of electrolysis.

It must not be concluded from the percentage of undissociated acid that the dissociation is absolutely permanent; for the ions of opposite sign attract each other with a force amounting to $(3{\cdot}4 \times 10^{-10})^2$ dynes when at a distance of 1 cm. apart and it

must happen that they occasionally meet and coalesce, in spite of the viscous resistance of the intervening water, and the peculiar effectiveness of the water molecules in splitting up molecules of other bodies. With a solution as dilute as we have above supposed, there are some 50,000 molecules of water to every molecule of hydrochloric acid, and such is the dissociating power possessed by this quantity of water that only one molecule HCl out of a hundred escapes dissociation. If, therefore, two ions of the acid consisting of hydrogen atoms which have lost one electron, and chlorine atoms which have gained one electron, should happen to meet and coalesce, they would again be dissociated before long. We may suppose that all the ions do meet and combine, but that for every second they spend in combination they spend one minute and thirty-nine seconds in separation, so that, on the whole, there are always ninety-nine out of every hundred of them dissociated.

This state of things is radically different from the case of a metal, where, as we have seen in the case of copper, each electron is combined with a positive atom about 5000 times longer than the time it spends flying free. From this we might at first sight conclude that the conductivity of copper was 5000 times less than that of a dilute solution of hydrochloric acid; but that conclusion would be quite unjustified. In the first place, it must be

remembered that conduction in copper is due, not to charged atoms, but to free electrons, which are a hundred-thousand times smaller, and therefore very much more mobile than charged atoms. Not only are they smaller in size, but the mass of an electron is also about a thousand times smaller than that of a hydrogen atom, so that the same force produces in it a thousand times more of an acceleration than in the hydrogen atom. An E.M.F. which in a metal would make the electrons move with a steady velocity of something like a kilometre per second, would only suffice to impart a velocity of $\frac{1}{300}$ cm. per second to the hydrogen ions in an aqueous solution. Since the value of the charge is the same in both cases, the currents will differ enormously in strength, the copper evincing by far the greater conductivity.

FIG. 17.

We may now proceed to consider in detail the behaviour of a cube of a dilute solution of hydrochloric acid with a side 1 cm. long, introduced between two infinite conducting plates kept at a difference of potential of 1 volt ($=\frac{1}{300}$ electrostatic unit).

Its weight may be put down as one gramme, being nearly the same as water. As regards its molecular structure, it consists of water molecules, H_2O, dissociated water molecules, $H+HO$, dissociated mole-

cules of hydrochloric acid, H + Cl, and undissociated molecules of the same, HCl. If the concentration of HCl is one-thousandth "gramme-molecule" per litre,[1] or one-thousandth of the "normal" concentration, the percentage of HCl in solution will be 0·00365. We may then put down the following census of molecules and ions contained in the cubic centimetre of solution:—

Neutral molecules of water H_2O	5×10^{22}
Total molecules of acid	$1·81 \times 10^{18}$
Of these dissociated H + Cl	$1·8 \times 10^{18}$
Of these undissociated HCl	2×10^{16}
Dissociated molecules of water H + HO . .	10^{14}

Of these constituents, only the dissociated ions play any part in the conduction of electricity, and of these there are 18,000 derived from the acid for one derived from water. Hence we are practically reduced to the hydrogen and chlorine ions if we wish to conduct electricity through the solution.

These must be present in equal numbers, as otherwise the solution would have a charge. Thus, if there were 1,000,001 hydrogen ions for every 1,000,000 chlorine ions, the solution could have a positive charge equivalent to 310 companies, which would charge it to a potential of over 100,000 volts.

[1] A solution is said to contain one gramme-molecule per litre if it contains M grammes per litre, M being the molecular weight of the substance. That of HCl being 35·5 + 1 = 36·5, the weight in one litre of water must be 36·5 grammes to give a "normal" solution of one gramme-molecule. The water weighing 1000 grammes, the percentage is 3·65.

Of the $1 \cdot 8 \times 10^{18}$ ions of hydrogen and chlorine, we must have, therefore, $0 \cdot 9 \times 10^{8}$ hydrogen ions, and the same number of chlorine ions. Each of the former has a positive charge equal to that of one positive atom, and each of the chlorine ions has a negative charge equal to that of one electron. The simple hydrogen ion is a positive atom—*i.e.* an atom deprived of one electron. The simple chlorine ion is a "negative atom"—*i.e.* an atom provided with an extra electron. But these charged atoms do not travel singly through the water. Their motions under the influence of electric force are so slow that the only plausible explanation seems to be that they are bound up with a number of neutral water molecules which act as a drag, and hinder their progress through the water. They are, so to speak. "hydrated," and the chlorine atoms are hydrated four or five times more heavily than the hydrogen atoms, and are therefore four or five times slower. If this were not so, it would be impossible to account for the slowness of the ions, for the water molecules are twice as loosely packed as the atoms in the copper. There is plenty of room between them, and hydrogen atoms, though so much larger than electrons, would have a reasonably long free path if they travelled singly. As it is, the hydrogen ions are the fastest of all ions known, the next being the ions of the combination HO, which, however, are only half as fast. The mobility of these main

constituents of water accounts for many of those characteristic qualities which make it the main vehicle of the processes of life.

Whatever the amount of hydration may be—and its absolute amount is difficult to calculate—it is a constant quantity for the same ion at the same temperature, whatever the chemical body from which it may be derived. The "mobility" of the ion is always the same at a given temperature. It is measured by the steady velocity it acquires under the influence of a "field" of one volt per centimetre—*i.e.* an electric field of force in which the potential varies by one volt for every centimetre travelled in the direction of the force.

Arrhenius, in his "Textbook of Electrochemistry," gives the following table of absolute velocities of the most commonly occurring ions at a temperature of 18°, under the influence of a fall of potential of 1 volt per centimetre:—

Cations.		Anions.	
H	3250×10^{-6}	OH	1780
K	670 "	Cl	678
Na	451 "	I	685
Li	347 "	NO_3	640
NH_4	660 "	CH_3CO_2	350
Ag	570 "	$C_2H_5CO_2$	320

The "cations" are those ions which take a positive charge (*i.e.* lose one electron) and wander to the cathode or negative plate. The "anions" are those

which take a negative charge—*i.e.* an extra electron—and wander to the anode or positive plate.

"From these data," proceeds Arrhenius, "we can calculate the mechanical force necessary to drive a gramme-ion[1] through the water with a certain velocity. The volt is so defined that the work 10^7 ergs is required to transport 1 coulomb against this potential difference. Inversely, if the fall of potential is 1 volt per centimetre, then 10^7 dyne-cms. (ergs) are required to transport 1 coulomb through 1 cm. against this fall—*i.e.* the force necessary for 1 coulomb is 10^7 dynes = 10·18 kilogrammes. The force required for a gramme-ion charged with 96,500 coulombs against the same fall of potential is therefore

$$96{,}500 \times 10{\cdot}18 = 983{,}000 \text{ kilogrammes.}$$

This force drives a gramme-ion of hydrogen with a velocity 325×10^{-5} cm. per second. The force required in order that the velocity may be 1 cm. per second must be $\frac{10^5}{325}$ times greater—*i.e.* it must be

$$\frac{983{,}000 \times 10^5}{325} = 302 \times 10^6 \text{ kilogrammes.}$$

The following table gives the force in million

[1] A gramme-ion contains as many grammes of the substance as its simple ion is heavier than an atom of hydrogen. In other words, it consists always of 0·9 quadrillion ions.

kilogrammes required to drive 1 gramme-ion through water at 18° with a velocity of 1 cm. per second:—

K	1467	Cl	1450
Na . . .	2180	I	1435
Li	2833	NO_3 . . .	1536
NH_4 . . .	1490	OH . . .	552
H	302	CH_3CO_2 . .	2810
Ag . . .	1725	$C_2H_5CO_2$.	3110

"From these numbers it can be seen what enormous mechanical forces are required to move the ions through the solvent with an appreciable velocity. As the temperature rises, these values, which are a measure of the friction, decrease in about the same ratio as that in which the mobilities of the ions increase—*i.e.* for most ions about 2·5 per cent. per degree.

"The electrolytic friction of the ions is greater in other solvents than in water. The addition of a very small quantity of another non-conductor to the water appreciably increases the friction of the ions, and consequently diminishes the conductivity of the solution, just as the internal friction of the liquid is altered by a similar addition. The action of foreign substances on the internal friction runs almost parallel with that on the electrolytic friction. Thus I have found that the addition of 1 per cent. by volume of alcohol, ether, acetone, or cane sugar raises the internal friction, and the electrolytic friction of the commonly occurring ions at 25° by the amounts quoted. If greater quantities be added

there is a proportional increase in the electrolytic friction; but also a diminution of the degree of dissociation of the electrolyte, particularly if a concentrated solution of this is used."

These remarks of the great Swede show that the two factors which determine conductivity—viz. density of ions and mobility—may both be affected by substances which increase the viscosity of the solution. But as long as these are absent. we may rely upon the constancy of that most important factor, the mobility of the individual ion.

That being so, we may proceed to calculate the electric current which will traverse the cubic centimetre of dilute solution we are contemplating. This current consists of two streams of electrified matter. One of these is the procession of positive H ions towards the cathode, and the other is the procession of negative Cl ions towards the anode. If we make any section across the lines of flow, a certain number of H ions will pass that section in one direction every second, and a certain number—a smaller number—of Cl ions will pass it in the other direction. The sum of these two numbers is the electric current.

The two processions result in an accumulation of H atoms at the cathode, and of Cl atoms at the anode. But for the first second of time, at all events, this accumulation will be small, and may be neglected, as also may be the emptying of the

neighbourhood of the anode as regards H atoms. For the first stages we may suppose the whole of the ions to be in motion.

The total number of H ions being $0{\cdot}9 \times 10^{18}$, and their mobility 0·00325, the proportion of them which traverses any section will be $0{\cdot}9 \times 10^{18} \times 0{\cdot}00325$ per second, or $2{\cdot}77 \times 10^{15}$ ions per second. Since 1 ampère is a current of $8{\cdot}79 \times 10^{18}$ electrons per second, the above current is equivalent to $3{\cdot}15 \times 10^{-4}$ ampère. This then is the positive current. The negative current consists of chlorine ions, $0{\cdot}9 \times 10^{18}$ in number, and having a mobility of 0·00068 cm. per sec. The current due to them is, therefore, $0{\cdot}9 \times 10^{18} \times 0{\cdot}00068$ electrons, or $0{\cdot}61 \times 10^{15}$ electrons per second, which amounts to $0{\cdot}69 \times 10^{-4}$ ampère.

Hence we have as a net result :—

Positive current . .	$3{\cdot}15 \times 10^{-4}$ ampère
Negative current . .	$0{\cdot}69 \times 10^{-4}$ ampère
Total current . .	$3{\cdot}84 \times 10^{-4}$ ampère

or about one-third of a milliampère.

This calculation is fully confirmed by experiment, and affords a very striking example of how the atomic theory of electricity may be applied to obtain a clear insight into what actually happens in an electrolytic cell. The clearness of the theory in this connection is due to the very definite data which are available concerning the number of dissociated ions in solution. This knowledge is by no means so precise in the case

of either metals or gases, and we cannot, therefore, make similarly precise calculations for these. From the electrical point of view, the dilute solution is the best known of all substances.

The above calculation also gives us the resistance, the resistivity, the conductivity ("conductance") and specific conductivity of the solution.

A body is said to have a resistance of one ohm if an E.M.F. of one volt applied to its terminals produces in it a current of one ampère. The current in our case being only $3{\cdot}84 \times 10^{-4}$ ampère, the resistance is correspondingly greater, and amounts to $\frac{10^4}{3{\cdot}84} = 2600$ ohms. This is also the resistivity or specific resistance of the electrolyte, since that is defined as the resistance of 1 cm. cube. The conductivity is the reciprocal of this, or $3{\cdot}84 \times 10^{-4}$.

If, now, we increase the concentration of the solution, we also increase its conductivity, since more ions will be added to it. But the increase will not be in proportion to the concentration, as less and less ions will be dissociated. With one gramme-molecule of HCl per litre, the degree of dissociation will only be 59 per cent. instead of 99 as before. There will be 1000 times as many molecules, but the conductivity will only be increased in the proportion of 59,000 : 99 or 596 : 1. It will thus be $596 \times 3{\cdot}84 \times 10^{-4}$ or $0{\cdot}22$, so that the current passing will be about one-fifth of an ampère.

Our attention is next claimed by what happens at

the electrodes. The H atoms arrive at the negative plate, which contains a vast number of electrons ready to pass out of the metal into the solution on the slightest provocation. Such provocation is supplied by the H ions, which, having lost an electron each, are positively charged, and attract electrons out of the metal. When this takes place the positive atom of hydrogen becomes a neutral atom. It immediately disengages itself from the embrace of the water molecules which have clung to it during its charged state, attracted by some as yet mysterious force, and becomes an ordinary gas. As it accumulates, its pressure becomes such that the water can no longer hold it in solution, and it escapes from the water in the shape of bubbles.

At the anode the converse process happens meanwhile. The chlorine ion, having an electron to spare, lets it pass into the positively charged plate, which is poor in electrons, and the chlorine atom becomes an ordinarily neutral atom of chlorine gas. But since water can dissolve a great deal more chlorine than hydrogen, the chlorine remains in solution, and gradually diffuses from the anode towards the cathode. In any case, we get an evolution of hydrogen at the cathode, and chlorine at the anode. The original hydrochloric acid is decomposed into its constituents by this process of "electrolysis."

Faraday's "First Law of Electrolysis," maintains that *the quantity of substance decomposed is pro-*

portional to the quantity of electricity passing through. That this must be so is immediately evident from the nature of the process as above explained. We must bear in mind that dissociation and decomposition are not the same thing. The former gives us charged ions, the latter gives us neutral atoms and molecules. Every ion, having a definite charge of one electron, or the lack of it, must either receive an electron from the cathode or give it up to the anode before it can become a neutral atom. Both processes involve a passing of an electron in the same direction, and therefore a definite "quantity of electricity passing through." Thus Faraday's First Law is self-evident in the electron theory.

We have hitherto only dealt with hydrochloric acid, which presents a very simple case of electrolysis. Other cases are not so simple. Take the case of zinc chloride, $ZnCl_2$. Here we have a molecule consisting of three atoms instead of two. When that becomes dissociated, each of the two chlorine atoms will take away an electron from the common stock, and leave the Zn with two vacancies. Each zinc atom will therefore require two electrons to neutralise it, and the number of zinc atoms produced will be one-half the number of hydrogen atoms which would be produced by the same current. The power possessed by an atom of combining with one, two, three, or more simple atoms like those of hydrogen

or chlorine is called the "valency" of the atom. In the case of a metal, it is measured by the number of electrons it is capable of giving up, or, in other words, the number of elementary positive charges it is capable of acquiring. We see then that *the number of atoms of any substance liberated by the current is inversely proportional to the valency of the atom.*

If the atoms had all the same valency, the *weight* of the substance liberated would be simply proportional to the weight of their atoms. But as they have different valencies, we must divide the atomic weight by the valency. Chemists call this quotient the "chemical equivalent" of the substance. Thus we obtain Faraday's Second Law of Electrolysis: *The amount of any substance liberated by a given electric current in unit time is proportional to the chemical equivalent of the substance.*

The liberation of any gramme-equivalent (*i.e.* as many grammes as the chemical equivalent weighs in comparison with the hydrogen atom) requires the passage of 96,537 "armies" or coulombs of electrons. This is therefore the amount of electricity required to liberate 1 gramme of hydrogen, 35·5 grammes of chlorine, 8 grammes of oxygen, or 31·5 grammes of copper.

When the two ions have the same mobilities, the substances liberated at the two ions will have the same concentration. This happens, for instance, in the case of potassium sulphate, where the K and SO_4

ions have the same mobility. But in other cases, as in that of HCl above considered, the migration of H away from the anode and towards the cathode will be much more rapid than that of the Cl towards the anode. The net result will be that, on the whole, the acid will gravitate towards the cathode, and leave the solution about the anode impoverished.

In the case of copper sulphate, on the other hand, the salt is used up more rapidly at the cathode than at the anode. For the mobility of Cu is 0·00048, whereas that of SO_4 is 0·00069. The SO_4 ions clear off towards the anode more rapidly than the Cu ions do in the contrary direction, and the solution gets diluted at the cathode.

I must add a few words on the manner in which the ionisation is determined. It is found that a body dissolved in a liquid has a certain pressure, just as a gas has. The pressure is, in fact, the same as the substance would have if the liquid were removed and the molecules left suspended where they were. This pressure is called the "osmotic pressure," and can be exhibited by means of two communicating tubes separated by a membrane which lets water percolate through, but stops the dissolved substance. Such a membrane is called "semipermeable." Certain kinds of parchment paper act as such membranes with regard to sugar. Now, if a solution of sugar is put into one of the communicating tubes and pure water into the other, the level of the sugar solution

is gradually seen to rise. It sucks water through the membrane, and the sugar molecules are thus enabled to occupy a larger volume than before.

The dissolved substances obey most of the laws of gases, like those of Boyle, Gay-Lussac, and Avogadro. The law of these maintains that the same volume of any solution at the same temperature, and having the same osmotic pressure, always contains the same number of molecules or ions.

This law gives us a means of determining the number of ions in a solution. For all ions act osmotically as separate molecules. We need only, therefore, determine the apparent increase in the number of molecules in order to be able to follow the gradual dissociation of the molecules as dilution proceeds. An important corroboration of the results thus arrived at is by determining the lowering of the freezing-point of solutions or the raising of their boiling-point with increasing concentration. The dissociations calculated from these experiments lead to the same results as those derived from observations of osmotic pressure and of conductivity.

6. *Discharge through a Vacuum.*—An electrified body can only be discharged through a vacuum if charges can be projected out of the body into the vacuum. For a vacuum by itself is a perfect insulator. It does not convey electricity, for the same reason that an empty can does not convey water—it does not contain any. If the electrified body is

brought into touch with a conductor, the swarms of loose electrons in the conductor and the charged body traverse the junction in one direction or the other until the body is discharged, or the charge divided between the two conductors according to their capacities. If a solution of an electrolyte is interposed between them, equilibrium is established by a migration of ions in both directions through the liquid. If a gas intervenes, the exchange is carried on by means of any electrons or heavier ions that may happen to be in the gas, or that may be produced by collision or other ionising agency. But these facilities are not available when a perfect vacuum intervenes between two conductors at different potentials. The only bodies capable of furnishing carriers of electricity are the conductors themselves. Now it is found that, although a conductor may be charged to a potential of thousands of volts, it is not easily discharged into a vacuum. The extra electrons, or positive atoms, never number more than one in a million; but they are all on the surface of the conductor on account of their mutual repulsion.

Why, then, do they not leave it and fly out into the vacuum? The force that holds them back is not yet fully explained; but it is the same force as that which prevents ions in a solution from separating out before they are discharged. These ions condense the liquid round themselves as long

as they are charged. They attract the neutral liquid, and the neutral liquid attracts them, holding them fast until they lose their charges at the opposite electrode. When ions happen to be contained in a moist gas, they act as centres of condensation, and it has been suggested that our whole rainfall is due to ions in the atmosphere, chiefly negative ions as well as electrons. This condensing action is, no doubt, also active in metals, and offers a certain hindrance to the free expulsion of the charge from a conductor into a vacuum. When a charged liquid is boiled, the vapour carries off none of the charge.

Ultra-violet light has a powerful effect in facilitating the discharge of electrons from negatively charged conductors, and entirely overcoming the hindrance ordinarily experienced. The light-waves may be conceived as shaking up the neutral atoms condensed round the electron, and setting the latter free.

Now, suppose we have two conductors in a vacuum at a difference of potential of one electrostatic unit (300 volts), and that by the action of ultra-violet light or other agency the electrons in the negative conductor are set free to enter the vacuum. They will, of course, be repelled by the negative conductor, and attracted by the positive conductor, and, since nothing is stopping them, they will fall freely from one to the other, and we can calculate their velocity by the well-known laws of

falling bodies. But a simpler way is to calculate their energy, and deduce the velocity from that. The energy required to drive one "company" (or "electrostatic unit") of electrons against one unit difference of potential, or 300 volts, is 1 erg. When the same company falls freely through the same difference of potential its kinetic energy is therefore also 1 erg. A single electron, possessing as it does a charge of $3{\cdot}4 \times 10^{-10}$ units, will have a kinetic energy of $3{\cdot}4 \times 10^{-10}$ ergs, and this, as we know, is equal to half its mass multiplied by the square of its velocity—

$$3{\cdot}4 \times 10^{-10} = \tfrac{1}{2} m v^2.$$

Now m is $0{\cdot}61 \times 10^{-27}$ of a gramme, hence we know v—

$$v^2 = \frac{2 \times 3{\cdot}4 \times 10^{-10}}{0{\cdot}61 \times 10^{-27}} = 1{\cdot}12 \times 10^{18}$$

and

$$v = 1{\cdot}06 \times 10^9 \text{ cm. per sec.}$$

This is truly an astonishing velocity, 6600 miles per second! It is about one-thirtieth of the velocity of light. But strange as it may seem, such a velocity has been *actually observed* in vacuum tubes. Had the Newtonian opponents of the wave-theory of light been acquainted with this remarkable fact, the corpuscular theory of light would have died harder than it did.

Since the velocity varies as the square root of the difference of potential traversed, it would theoreti-

cally require 30^2 or 900 times 300 volts to impart a speed equal to that of light to the electrons. The voltage could be obtained, perhaps; but it would not have the desired effect, since the resistance of the ether to the motion of a very fast electron is very considerable, and becomes infinite near the speed of light.

Electrons projected with such velocities as these are known as *cathode rays*. They were discovered by Plucker in 1858, and described by Crookes in 1879 under the name of "radiant matter," a name which was much more appropriate than the scientific world was inclined to believe at the time, or, indeed, for many years after. Crookes, however, thought the rays consisted of atoms, which were then considered the smallest possible bodies in the universe. Nowadays the cathode rays would be more appropriately styled "radiant electricity." They are produced in a glass tube exhausted to one-millionth of an atmosphere, thus leaving only 40 billion molecules of gas per cubic cm. Crookes showed that they proceed in straight lines at right angles to the surface whence they spring, that an obstacle placed in their way casts a sharp shadow; that they produce a vivid phosphorescence when impinging upon glass, or especially jewels; that they exert a mechanical pressure where they fall, and that they can be deflected by a magnet. To these important properties we must now add the still more remarkable

property of producing Röntgen rays when they impinge upon a solid body.

Positively charged bodies can also be discharged through a vacuum; but as there are no positive electrons, the smallest positive carriers are of atomic dimensions, and are at least 1000 times heavier than electrons. Since the charge of a positive atom is the same as that of an electron, the electric force upon it is also the same. But this force, having to set in motion a body at least 1000 times heavier than an electron, will produce in it a velocity at least 1000 times less. Wien has actually found a group of positive ions having one-thousandth of the velocity of electrons, another having one twenty-thousandth, and another having one-millionth of their velocity. The last of these must consist of groups of neutral atoms combined with one positive atom each. Positive ions moving with these comparatively high velocities are called "canal rays," since they are best observed by perforating the cathode, and letting them emerge on the other side. It is interesting to note that material particles of atomic dimensions can be endowed with a velocity of six miles per second by a human agency. This speed is about twice the velocity of a point at the Equator due to the earth's rotation.

The prodigious velocities acquired by charged particles in a vacuum probably play a very important part in the electric equilibrium of the

universe. Consider one or two points. The difference of potential between the earth and the sun is about a billion volts, the sun being positive and the earth negative. Any electrons expelled from the earth will therefore travel towards the sun with a constantly increasing speed, and will travel with a velocity nearly equal to that of light over the last stages. Its kinetic energy will go to keep up the sun's heat. When it gets into the neighbourhood of the sun it will exert its condensing action upon the neutral gases there, and will form a small drop. This drop will be exposed to the radiation of the sun, which, according to Maxwell and Bartoli, exerts a pressure sufficient to balance the weight of a very small drop. The maximum pressure in comparison with weight is exerted on a drop 8×10^{-6} cm. in radius, and having the density and capacity of water. The radiation pressure is then 2·5 times the gravitational attraction. Such drops are constantly being repelled from the sun in enormous numbers. Their expulsion keeps up the sun's positive charge; but that positive charge does not increase indefinitely, since the sun drains vast tracts of space of the electrons which abound in them. Arrhenius has estimated that the sun drains the space as far out as one-sixtieth of the distance of the nearest fixed star of its free electrons, and thus maintains a constant circulation of electricity throughout the solar system.

CHAPTER V

THERMO-ELECTRICITY

We will now return to metallic conductors in order to study the effect which heat exerts upon the distribution and motion of electrons in them.

The modern view of heat is that it is a rapid motion of the smallest particles of matter. Before the days of the electron theory, these smallest particles were supposed to be atoms. We now know that atoms are not the smallest existing particles; but the electrons, which are at least as numerous as the atoms in a metal, are at least one thousand times lighter, and about a hundred thousand times smaller. The equality of temperature throughout the metallic mass means that the average kinetic energy of the particles of all kinds is the same in any small volume chosen at random. Now, since the kinetic energy of a body is $\frac{1}{2}mv^2$, where m is its mass and v its velocity, two bodies at the same temperature must have the same velocity if their masses are equal; or, if they are unequal, their velocities must compensate such inequality. If the mass of one body is one-fourth of that of another body, the square of its velocity must be four times

as large, and its velocity must be twice as large. Now, since the mass of the electron is about $\frac{1}{56000}$ of that of an iron atom, its velocity at the same temperature must be 240 times as great.

The absolute temperature varies as the square of the velocity of the particles. The "absolute" temperature in degrees centigrade is reckoned from the absolute zero of temperature, which is 273° below freezing-point. Thus the absolute temperature of melting ice is 273°, and of boiling water 373°. Hence, the velocities of the particles at freezing-point and boiling-point will be as

$$\sqrt{273} : \sqrt{373}, \text{ or } 16{\cdot}5 : 19{\cdot}3.$$

In heating a wire from the freezing-point to the boiling-point of water, the velocity of all its atoms and electrons is increased 17 per cent.

Now we have seen that the electrons behave practically like a gas capable of penetrating the metal. When they are heated it is just as if the pressure of a gas were increased by heating it. Their pressure is also increased, and they make their way into cooler parts, where the pressure is less.

Here, then, we have a displacement of electrons, and we know that a displacement of electrons constitutes an electric current. It is therefore possible to generate an electric current by heating a metal unequally in different parts.

If the wire is bent into a ring, and it is heated at one point, electron currents in opposite directions will start from the hot point. There will, of course, be no current round the circuit, since the two opposed currents neutralise each other. But if the wire on one side of the hot point is kept cool in a water-jacket, the slope of pressure will be more abrupt on that side, and the electrons will pass by preference in that direction. There will, therefore, be a resultant electron current in the direction of the water-jacket, or a positive current in the reverse direction. Any other means of making the slope of temperature and kinetic pressure more abrupt will have the same effect. Thus, if the wire is passed slowly through a flame, leaving a steeper gradient of temperature in front than behind, the electron current will flow in the direction in which the flame moves along the wire.

Conversely, if an electron current is sent along a wire containing a hot point, it will carry the heat along with it, producing a more gradual slope of heat on the other side of the hot point. This may be well observed in an iron wire.

The simplest way of altering the slope of the heat-curve is by joining two metals of different conductivities for heat. Thus, if (Fig. 18) a bar of lead and a bar of zinc are joined at A and heated at the junction, the slope of temperature will be more abrupt on the lead side than on the zinc side,

and an electron current will pass steadily from the zinc to the lead and back through the wire outside. Or, to use the older language, a (positive) current will pass across the hot junction from lead to zinc.

If we leave the zinc-lead junction cool, and send an electron current through it from the zinc to the lead, it is evident that the same number of electrons

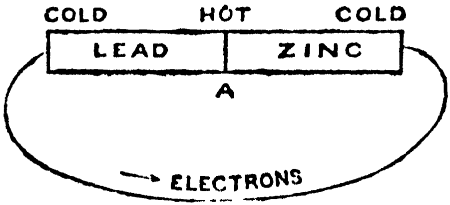

FIG. 18.

must pass every cross-section both of the lead and the zinc. Since there is more resistance to be overcome in the lead than in the zinc, the electrons entering the lead must acquire an extra supply of energy, and this can only be derived from the motion of the atoms and electrons themselves. Hence the junction A will be cooled. An electron current in the reverse direction would heat the same junction. This heating and cooling of junctions of dissimilar metals by a current passing through is known as the Peltier effect.

All the above reasonings have supposed that the heating and cooling have no effect upon the electric conductivity of the metal, nor upon its two factors

—viz. the density and mobility of the electrons. But in reality both these factors are profoundly affected by heat, and the actual phenomena are therefore more complicated than the above reasoning might lead us to suppose. Before we are in a position to deal fully with thermo-electric phenomena, we must have some more information concerning these two factors, and must also consider the difference of potential between two metals or other conductors produced by contact at ordinary temperatures.

I have indicated the general principles upon which a full theory of thermo-electric effects must be based. But this full theory is by no means worked out as yet. The older theories stood quite helpless before the puzzling variety of thermo-electric phenomena. The electron theory gives us valuable help; but a great deal remains to be done, and the research student cannot choose a more promising field for his labours, or one more likely to give him a rich reward, than the connection between electricity and heat. The direct conversion of thermal into electrical energy—in other words, the generation of electricity direct from coal—is a problem fraught with great economic consequences. Thermo-electric batteries have been employed for some time in galvanoplastic and other small installations; but their efficiency and durability still leave much to be desired. Haphazard experiments are not likely to lead to any radical improvement without the

probability of a long series of costly failures. But a good working theory of thermo-electricity may indicate the lines along which success may be looked for with a reasonable degree of probability.

The fact discovered by Seebeck is that when a rod of antimony and a rod of bismuth are joined at one end and heated at that end, and the bismuth rod is bent round so as to join the antimony at the other end, and that junction is kept cool, a (positive) current flows across the hot junction from the bismuth to the antimony.

This means, according to the electron theory, that electrons travel across the hot junction from the antimony to the bismuth, and across the cold junction from the bismuth back to the antimony. There is no real "positive current," since that would need atoms for its transportation, and these could only be bismuth atoms travelling across the hot junction into the antimony. The end of the antimony would thus be converted into an alloy of bismuth and antimony. This has never been observed; but it has been found that under extreme pressure one metal may be forced to diffuse into another, and when that takes place a real positive or atomic current may pass. Under ordinary circumstances the electron current is the only electric current large enough to be measured. But we may suppose that a certain amount of atomic diffusion

does take place even at ordinary pressures, and to this atomic diffusion current we may attribute the gradual degeneration of thermo-electric batteries.

Antimony and bismuth show one of the largest thermo-electric effects known, and this fact no doubt facilitated its discovery by Seebeck. But all combinations of metals may be used for generating thermo-electric currents. The current-strength obtained varies from one metal to another. We know that the current is proportional to the conductivity and to the energy spent in driving an electron round the circuit, and we have seen that this energy-per-electron is called the electromotive "force" (E.M.F.). Now the E.M.F. generated by a bismuth-antimony couple whose junctions are kept at boiling-point and freezing-point respectively is $\frac{1}{200}$th of that of a Daniell cell, so that 200 couples would have to be ranged in series in order to give the E.M.F. of a single Daniell cell. Bismuth, being costly, and its resistivity high, such a battery would cost much more than the cell. But then a current could be obtained from it at any time by heating alternate junctions with boiling water or steam.

E. Becquerel in 1864 compared a large number of metals with copper, and measured the E.M.F.'s they yielded when combined with copper, with their junctions kept at freezing-point and boiling-point respectively. I quote his results:—

Bismuth	$-3{\cdot}91$	**Platinum**	$-0{\cdot}09$ to $0{\cdot}38$
Cobalt	$-2{\cdot}24$	**Zinc**	$-0{\cdot}02$ to $0{\cdot}04$
Nickel	$-1{\cdot}63$	**Copper**	0
German silver	$-1{\cdot}26$	**Silver**	$+0{\cdot}026$
Palladium	$-0{\cdot}82$	**Cadmium**	$+0{\cdot}033$
Mercury	$-0{\cdot}48$	**Iron**	$+0{\cdot}95$ to $0{\cdot}67$
Lead	$-0{\cdot}187$	**Antimony**	$+1{\cdot}41$
Tin	$-0{\cdot}147$	**Tellurium**	$+39{\cdot}95$
Gas carbon	$-0{\cdot}142$		

The figures mean thousandths of a Daniell (1 Daniell = 1·1 volt), and the negative sign indicates that the positive current flows across the hot junction from the metal in question to the copper—*i.e.* that copper yields electrons to the metals across the hot junction.

The E.M.F. of any two metals may be obtained by adding up the figures for each, if of opposite signs, or subtracting them, if of the same sign.

It will be seen at once that the commoner metals have very poor thermo-electric effects. A zinc-copper thermo-couple has only $\frac{1}{200}$th of the E.M.F. possessed by a bismuth-antimony couple, so that it would require 40,000 zinc-copper couples to make up an E.M.F. equal to that of a Daniell cell.

The thermo-electric force is, generally speaking, proportional to the difference of temperature between the junctions. The rise of the thermo-electric force with the temperature is so constant and reliable that a system of thermometry by thermo-couples has been based upon it. But some couples, notably the combinations with iron, show a gradual decrease of

the rise at higher temperatures, and at certain differences of temperature there is a zero thermo-electric force, or even a new force in the opposite direction.

Liebenow has found an important relation between the thermal and electric conductivities which enables us to predict the thermo-electric force of a combination of two metals with some certainty. He finds that the greater the conductivity for heat is in comparison with the conductivity for electricity, the more freely do electrons pass out from a metal across a hot junction. He also finds that there is an E.M.F. generated within the metal itself which urges the electrons to proceed in the direction in which heat is being propagated. This is just as we should expect. The E.M.F. of the thermo-couple is a differential effect, due to more electrons being dragged along by the heat in one metal than in another. If L is the conductivity for heat and S the electric conductivity, the E.M.F. between two portions of the same metal kept at two different temperatures, say at boiling-point and freezing-point, is proportional to $\sqrt{\frac{L}{S}}$. This means that whatever affects the two conductivities also affects the E.M.F. of the metal concerned. Now we know that the resistance of a metal increases with the temperature; that is to say, the conductivity diminishes as the temperature rises. Hence the

above ratio will increase with heating, if the thermal conductivity remains constant. This is very generally the case, and whatever may be the difference between two metals in their internal thermo-electric forces, that difference is, as a rule, exaggerated on further heating. But in some metals the difference tends to disappear on heating, or to be reversed, and then the E.M.F. of the couple passes through a maximum, and then diminishes.

To help us in our search for the ideal thermo-couple—an ideal which, once realised, would be of the utmost practical importance—we may say that what we want is two metals in which the ratio $\sqrt{\frac{L}{S}}$ is as different as possible. For instance, one of them might have a very high, and the other a very low, conductivity for heat in comparison with its electric conductivity. Antimony has a high, and bismuth a low ratio.

Another desideratum is that the ratios of the two metals shall not tend to become equal as the temperature rises. For then a point (called the "neutral point") would be reached at which the wandering of the electrons would be the same in both directions away from the hot junction, and none would traverse the junction. There would be no electron current, and hence also no "positive current."

The ratio depends essentially upon the energy of the carriers of thermal and electric energy in

proportion to their absolute temperature. The carrier of the electrical energy is the electron, having a mass of 10^{-27} gramme, which we will call m. The carriers of thermal energy are both atoms and electrons. If they are mainly atoms, we may put their mass M at about 60,000 times that of the electrons. Finally, if T is the absolute temperature (*i.e.* 273 + the degrees centigrade), then we have the internal thermo-electric force in a metal proportional to $\frac{\sqrt{mM}}{T}$. The best thermo-electric effect would therefore be obtained by combining two metals differing in such a manner that this ratio would be great in one and small in another. Now that ratio is, as we have seen, small in bismuth. The mass of the carriers of heat is small. This means either that there are few atomic clusters, or that the electrons themselves diffuse the major part of the thermal energy. In antimony, on the other hand, the carriers of heat are mainly larger masses. There is more energy in a gramme of antimony that in a gramme of bismuth at the same temperature. Hence the electrons, always tending to expend their energy as rapidly as possible, pass by preference into the bismuth. At the cold junction, where the difference of energy is not so marked, the electrons must, perforce, return into the antimony under pressure from the hot junction, and so the circuit is completed.

When, on the other hand, an independent current is sent across a junction from bismuth to antimony, the increased energy in the antimony is generated by absorption of heat at the junction. This is the Peltier effect. The cooling of the junction in its turn

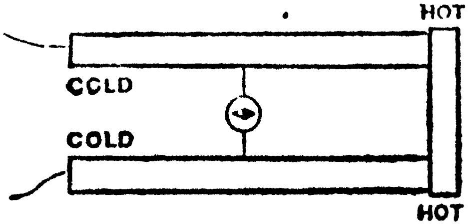

FIG. 19.

generates a current in the direction opposed to the original current. This is an instance of the well-known rule that whatever action an electric current may exert, that action acts contrary to the current. To put it briefly, all acts of an electric current are suicidal.

To sum up, we have three thermo-electric effects. The first, that discovered by Seebeck, shows an electric current generated by the unequal heating of the two junctions of two different metals. The second, that discovered by Peltier, shows the cooling of a junction of two different metals, which, if heated, would produce a current in the same direction. When the current is reversed, the junction is heated instead of being cooled.

The third effect is known as the Thomson or

Kelvin effect. It is really the most important effect of all, the others being merely differential effects. It consists in the transportation of electricity with a current of heat, and *vice versâ*. An ingenious experiment for exhibiting this effect has been devised by Le Roux. A current is sent through three bars of copper, placed as shown in the figure. The junctions on the right-hand side are heated, while the other ends are cooled. There can be no Seebeck effect, as the metal is everywhere the same. But in one bar the electric current goes from cold to hot, in the other from hot to cold. In one bar it opposes the heat current, in the other it aids it. As a consequence, the heat travels faster in one bar than in the other, and disturbs the even flow of the electric current. A galvanometer connected as shown, and made to show no deflection when the junctions are all at the same temperature, shows a permanent deflection when heat is applied, thus indicating that a current has been diverted into it.

CHAPTER VI

VOLTAIC ELECTRICITY

UNDER the name Voltaic Electricity are comprised a number of phenomena which depend upon differences in the behaviour of bodies towards electricity apart from effects of temperature, magnetism, and other factors.

These phenomena are connected with the most intimate internal structure of the elements, and are therefore of great variety, and of some uncertainty, being often profoundly affected by surface conditions and by slight impurities. But in the hundred years since Volta discovered contact electricity, much has been done in the way of establishing the general principles which underlie the phenomena, and which indicate their connection with chemical reactions.

Electrification by Contact.—The fundamental fact discovered by Volta in 1797 is that when a piece of zinc touches a piece of copper, a spontaneous charge of both metals takes place, the zinc being charged positively and the copper negatively.

Since the combination of the two metals exerts no electrical force at a distance, the positive electrification of the zinc must be exactly equal to the

negative electrification of the copper. This, when stated in the language of the electron theory, amounts to saying that a certain number of electrons have passed across the point of contact from the zinc to the copper. When the metals are separated, their charges become more evident, being no longer neutralised by each other. The charges can be removed by connecting the metals to earth. In other words, when the metals are connected with, say, a water-pipe, electrons pass from the earth into the zinc, and from the copper into the earth, until copper, zinc, and earth are again at the same potential. The process can then be repeated indefinitely, always with the same result.

We may state the result by saying that copper exerts a greater attraction upon electrons than zinc. Hence, when electrons pass from zinc to copper, work is done upon them, just as it is done upon them when they pass from a negatively to a positively charged body—*i.e.* from a body having an excess of electrons to a body having a deficiency of electrons. There is thus a natural or inherent difference of potential between them, which only comes into operation when they are brought into contact, and which then leads to the passage of electrons from the zinc to the copper. This passage continues until the positive charge of the zinc and the negative charge of the copper become so large that the potentials due to them just balance the natural

difference of potential. The potential due to the newly acquired charges thus forms a measure of the natural difference of potential, and is called the "contact potential" between the two metals. This contact potential is found to be constant for the same two specimens, subject to slight fluctuations with temperature and surface condition. It amounts to about three-quarters of a volt in the case of ordinary commercial copper and zinc. This means that when one "company" of electrons (*i.e.* one electrostatic unit of negative electricity) passes from originally uncharged zinc to uncharged copper across the junction, the amount of work done upon it, and frittered away into heat, is $\frac{1}{400}$th of a dyne.

The larger the surfaces of the metals, and the smaller their distance apart, the larger is their "capacity" (p. 58) regarded as a condenser. Hence also the larger is the amount of electricity which must pass in order to bring up the difference of potential to the amount required to balance the natural difference of potential. Therefore, although the contact potential is a constant quantity, the actual charge of the metals depends upon their dimensions and upon the intimacy of their contact. This fact sheds considerable light upon electrification by friction, where the rubbing of one body over another increases the charge of each.

We must next endeavour to account for the fact

that zinc has a greater tendency than copper to get rid of its electrons.

We have seen above (p. 110) that metallic atoms have a tendency to get rid of one or two electrons each whenever they can find a non-metallic atom ready to take up the electrons they themselves can spare.

When zinc is immersed in a dilute solution of one of its own salts—say, zinc chloride—the atoms of the zinc have a powerful tendency to pass into the liquid as positive ions. In endeavouring to do so, they must somehow dispose of their superfluous electrons. The zinc atoms already in solution are unable to take up electrons without neutralising and precipitating themselves, while the chlorine atoms are already in charge of the electrons given up by the dissolved zinc. The only alternative remaining is, therefore, to leave the electrons behind in the mass of the metal, which is thereupon charged negatively. Even when this negative charge is removed by connection with earth, the solution of the zinc cannot proceed much further, since the accumulation of positive zinc ions in the liquid charges the liquid positively, and thus prevents any further positive atoms from entering it. The positive charge of the liquid can be measured, and when that is done, it represents a measure of the strength of the tendency of zinc to give up its electrons and go into solution. This tendency is called the "solution-

pressure" of the zinc. It is very similar to the "vapour pressure" of a liquid, and like it, it can be measured in atmospheres. The solution-pressure of zinc is enormous: it is about a trillion atmospheres. That of copper, in copper sulphate, is very small, being about a trillionth of an atmosphere. No wonder, then, that when copper and zinc are brought into contact, the eagerness of the zinc to dispose of its electrons should exhibit itself in the extrusion of electrons from the zinc into the copper, thus producing the phenomenon observed by Volta.

The facility with which zinc loses its electrons is shown in a striking manner by some recent experiments of Fuechtbauer. He produced a stream of "canal rays," or positive gaseous ions, in a vacuum tube, and let that stream impinge upon various metals. He found that the metals, which were platinum, silver, copper, zinc, and aluminium, all gave off electrons under the impact of the canal rays; but that the electron current from the copper was to that from the zinc in the ratio of 128 to 192. A still greater current (305) was obtained from aluminium; but the behaviour of this metal depends very largely upon its surface condition. When polished with oil and pumice, it is more positive than zinc, and therefore gives off electrons still more easily; when cleaned with water and dried in air, it is less positive than zinc.

Another set of phenomena which go to explain

contact electricity is that of discharge by ultra-violet light. This remarkable phenomenon, discovered by Hertz, and studied in detail by Elster and Geitel, Stark, and others, consists in the spontaneous discharge of a negatively charged body when illuminated by ultra-violet light. It may be exhibited as follows: A well-cleaned zinc plate is mounted vertically, and exposed at short range to the light of an arc lamp or an intense electric spark, both of which contain abundant ultra-violet rays. The zinc plate is connected with a sensitive electrometer. This then indicates a positive charge after a short time. This gradually increases, and may reach 30 volts if air is blown against it, in order to remove the expelled electrons to a distance. This shows that the zinc plate has given off negative electricity—*i.e.* electrons. The conclusion is confirmed by sucking the gas near the plate through a metallic tube containing a plug of glass wool at the other end. The tube becomes negatively charged, owing to the absorption of the electrons by its wall.

If the zinc plate is negatively charged to begin with, it loses its charge very gradually in the dark. But, if an earthed piece of copper or brass wire netting is placed over it, and it is illuminated with ultra-violet light through the network, the charge is rapidly dissipated. A positive charge is not affected in this manner. If the copper netting is connected

through a galvanometer and a battery with the zinc in such a manner that the zinc is negatively charged, the galvanometer indicates an electron current passing steadily from the zinc to the copper and back through the battery as long as the illumination is kept up.

Such a current is called a "photo-electric current." Similar currents are exhibited by other metals besides zinc; but in copper and platinum, for instance, they are extremely feeble, owing to the tenacity with which they retain their electrons.

Volta arranged a number of metals in a series in such a manner that any metal combined with any other metal further on in the series would be positively charged. The Volta series is: Zinc, lead, tin, iron, copper, silver, gold. He found, further, that the contact force between any two of them was equal to the sum of the contact forces of the intermediate pairs. This is fairly obvious, since the drop of potential in passing from one metal to a second, and from the second to a third, must be equal to the rise of potential in passing from the third back to the first if there is to be conservation of energy. Otherwise an electron, by passing round in this manner, might be made to generate energy continuously out of nothing.

A more complete voltaic series is that given by Hankel as follows: Aluminium, zinc, cadmium, lead, tin, antimony, bismuth, German silver, brass,

mercury, iron, copper, gold, palladium, silver, coke, platinum.

That the voltaic series is determined by the ease with which the metals lose electrons is proved by the fact that the same series governs—

(*a*) The solution pressure of a metal immersed in a solution of one of its own salts;

(*b*) The photo-electric current from a metal; and

(*c*) The electron current from a metal when exposed to canal rays.

It may therefore be taken that the contact force between two metals, about which physicists have been contending for a hundred years, is now reduced to a simple principle, and that any further explanation must tell us why some metallic atoms hold electrons more firmly than others. A highly ingenious explanation of this has recently been attempted by J. J. Thomson, on the basis of the equilibrium of various configurations of electrons embedded in a sphere of positively electrified matter.[1] For the present, we will take the different attractions exerted by different metals upon the electron for granted.

Contact electrification is not confined to metals, but is practically universal, not only between dissimilar bodies, but between the same bodies having a slight difference of structure or surface condition. We have already seen that a kind of contact E.M.F. exists between two portions of the same body which

[1] See "Electrcity and Matter," by J. J. Thomson.

are at different temperatures, the only difference being that the difference of temperature has to be artificially maintained.

Non-conductors also exhibit decided contact forces. They may be determined by mounting them between different metals. Thus, when paraffin-wax is poured between plates of copper and zinc, the plates acquire a certain difference of potential, which represents the sum of the contact forces between copper and paraffin, and paraffin and zinc respectively.

Frictional Electricity.—That frictional electrification is simply a form of voltaic electricity is evident from the fact that the electrification by friction is of the same sign as the electrification by contact. But frictional electrification is even more sensitive to surface conditions than contact electrification, no doubt because the intimacy of contact is much greater. The greater intimacy of contact, by increasing the capacity of the two bodies, also increases the charges they acquire through the same difference of potential. These charges may be very high, and are confined to smaller areas in non-conductors than in conductors, owing to the fact that the latter distribute the charges uniformly over their surfaces. Hence it may happen that when two non-conductors are separated after being rubbed together, the charges are very strong, and lead to sparking and spluttering. This circumstance explains why electrification by friction was the first from of electrification discovered.

Attempts have been made to arrange substances in a series corresponding to Volta's series, in such a manner that any one of them, rubbed against any subsequent one, is positively electrified. The series given by Faraday is the following: Catskin, flannel, ivory, quill pens, rock crystal, flint glass, cotton, canvas, white silk, the hand, wood, lacquer, metals (iron, copper, brass, tin, silver, platinum), sulphur.

It appears from this series that all metals lose their electrons less easily than most of the substances above enumerated. But caoutchouc, sealing-wax, sulphur, collodium, and guncotton are still more retentive of electrons, and therefore become negatively charged even by friction against silk. Gaugain has arranged the metals in a frictional series which corresponds closely to Volta's contact series.

The Galvanic Cell.—In all these contact electrifications there is no passage of one material into another. It is the electrons alone which pass, and the substance which loses electrons most easily becomes positively charged. But an entirely different state of things arises when a metal is immersed in a liquid capable of dissolving it. In this case it is the dissolved metal, and not the solid lump, which loses electrons in order to form hydrated ions, and as a general rule the electrons are gathered up by the lump of metal, which

thereby becomes negatively charged. The greater the solution pressure of the metal, and the greater its tendency to lose electrons, the greater will therefore be the number of electrons accumulated by the metal itself. This result appears strange until we realise that the zinc ions are the result of a clustering of the solvent round the zinc atoms—a clustering which means a loss of energy. Since the clustering, as we have seen, can only take place if the zinc atom is charged, and the zinc atom is incapable of taking up an extra electron, it must lose one or two electrons in order to get charged. Work must be done in order to draw the positive zinc atom out of the negatively charged metal, and the energy necessary for this work is furnished by the clustering of the molecules of the solvent. When, besides the zinc, another metal, say copper, is immersed in the same solvent, it may happen that the solution pressures of the two metals differ very widely. In that case the zinc will be much more highly charged with electrons than the copper, and if metallic connection is established between them, an electron current will pass from the zinc to the copper. In the older language this means that a current or "positive current" passes from the copper to the zinc. The passage of the current will continue until the excess of electrons is drained out of the zinc; but, as long as the zinc atoms

go on dissolving and giving up electrons to the zinc, a steady current will be maintained.

Take the case of an elementary galvanic cell, consisting of a plate of copper and a plate of zinc immersed in dilute sulphuric acid, and joined by a wire outside the liquid. The liquid consists of water molecules, acid molecules, H_2SO_4; positive ions, H; and negative ions, SO_4. Zinc atoms are constantly going into solution, and giving up their electrons to the zinc from which they issue. These electrons, flowing round the outside circuit into the copper, neutralise the H atoms in the neighbourhood of the copper, and liberate the hydrogen from the liquid in the form of bubbles. Thus, zinc disappears into the liquid on one side, and hydrogen leaves the liquid on the other side. Both zinc and hydrogen are positively electrified atoms, and we, therefore, have here a material "positive current," which, however, is only really in existence in the layers nearest to the electrode. The really continuous current in the outside circuit is the electron current. It is the only thing that moves in the wire.

All electric batteries work on the same principles as those above set forth. They only differ in the contrivances made to increase the difference of solution pressure, to facilitate the exchange of electrons, to reduce the resistance of the liquid, to insure the long continuance of the current, and to increase the convenience and economy of practical working.

CHAPTER VII

ELECTRO-DYNAMICS

Up to the present we have only considered such mutual forces of electrons as are playing between them when at rest. We have seen that one electron repels another placed near it at a distance of one centimetre with a force of $1 \cdot 16 \times 10^{-19}$ dynes, whatever material may intervene between them. The same force is exerted between two neutral atoms when they are deprived of one electron each, and thereby converted into "positive atoms." On the other hand, an electron *attracts* a positive atom with the same force.

These three forces are called electrostatic forces, because the electric bodies are at rest. We now proceed to consider the forces brought into play when the electric bodies are in motion.

When two electrons travel side by side through the ether, some of the repulsive force between them apparently disappears. The amount of repulsive force disappearing depends upon the velocity; it increases in direct proportion with the velocity, and when the electrons move with the velocity of light

the repulsive force disappears entirely, and the two electrons cease to exert any action upon each other.

The same change of force takes place when two positive atoms travel side by side through the ether.

Both these facts may be stated more clearly by saying that two electrons or two positive atoms (or similar charges of any kind) travelling side by side through the ether exhibit a mutual attraction which increases with the velocity, and which balances their electrostatic repulsion as soon as they travel with the velocity of light.

When an electron and a positive atom travel side by side through the ether, their original attraction is balanced by a mutual repulsion, so that again, when they travel with the velocity of light, they exert no mutual force. This implies that when a neutral atom travels so fast as to nearly approach the velocity of light, it becomes incapable of retaining its electrons, and becomes "ionised."

The facts form the basis of all the phenomena of electro-dynamics, of magnetism, and of induction.

The forces due to the steady motion of electrons, positive atoms, or charged bodies through the ether are called magnetic forces.

Take a long copper wire, 1 mm. in radius, stretch it across the room, and send a current of 1 ampère through it. What is the magnetic force due to the steady motion of its electrons?

In the first place, we must know something of the

velocity with which the electrons are travelling through the wire. They travel in a direction opposite to what was hitherto called "the electric current." They travel from the zinc to the copper of a cell, or generally from the negative to the positive-pole. There is no perceptible displacement of the positive or neutral copper atoms. They are firmly packed together, and cannot migrate, whereas the electrons thread their way between them and progress with a steady average speed, which is directly proportional to the electromotive force which drives them. Their motion constitutes the real electric current, and produces all the heating and magnetic effects which we associate with an electric current.

The passage of one ampère across any section of a wire means the passage of an "army" of 8·79 trillion electrons across that section every second (p. 90). This number of electrons, which, in order to emphasise the atomic conception, I have called an "army," is usually called a "coulomb" of negative electricity. It contains 3000 million "companies" or electrostatic units of electric quantity. One "company" contains 2930 million electrons. We may therefore say that an electric "army" contains about as many companies as the company contains men.

Let an army of electrons traverse the point A in the conductor AB. It takes one second to pass in

review at A. We want to know where its scouts will be by the time the rearguard has arrived at A.

In order to determine this, we simply have to find what length of the wire contains an army of electrons available for conveying electricity. We have estimated the number of available electrons in 1 cubic centimetre of copper at 380 trillion (p. 90). An army of 8·79 trillion is therefore contained in every $\frac{8{\cdot}79}{380}$ cc. or 0·023 cc. of copper.

FIG. 20.

Since the radius of the copper wire is 1 mm. its area is $0{\cdot}01\pi$ sq. cm., and its volume per cm. length is $0{\cdot}01\pi$ cubic centimetres, or 0·0314 cc.; therefore the length of copper required to contain an army of movable electrons is $\frac{0{\cdot}023}{0{\cdot}0314} = 0{\cdot}723$ cm.

Hence, by the time the rearguard passes A, the vanguard is 0·723 cm. ahead, and the rearguard will reach the same spot one second afterwards. In other words, the speed with which the army marches is 0·723 cm. per second.

This is the velocity of the electrons in a copper wire 2 mm. in diameter, carrying a current of 1 amp. Doubling the current means doubling the speed of the electrons, and, therefore, quadrupling their energy which varies as the square of the speed,

and quadrupling the heating. Doubling the resistance while the current remains the same also means doubling the speed; but since the number of electrons per unit length is halved, it only means simply doubling the heat evolved per unit length instead of quadrupling it. (Joule's Law.)

The magnetic force does not depend in any way upon the resistance of the wire, but simply upon the number and speed of the electrons—*i.e.* upon their momentum, $m v$.

The magnetic force may be tested by means of a small magnetic needle which sets itself at right angles to the current. That is the old familiar way of measuring a current. But in these articles we must proceed differently. Magnets, magnetism, and magnetisation are all to be reduced to the distribution and motion of electrons. A magnet is a highly complex system of spinning electrons. There is nothing fundamental about it. The fact that the electromagnetic system of units is based upon the definition of a unit magnetic pole simply exhibits the dire straits to which the older theories were reduced when brought face to face with magnetic force. The magnetic pole, being a thing whose true nature was unknown, had to be regarded as an elementary thing, not reducible to any other known principle, just as water was considered an element before Cavendish analysed it. Electric currents were measured by magnets, instead of *vice versâ*. In

the future science of electricity the magnetic pole will play a very subordinate part.

How, then, can we measure the magnetic force due to the electrons moving in the wire?

It is evident that the electrons alone produce the magnetic force; for the positive atoms are at rest. They are equal in number to the electrons, and therefore the wire has no electric charge as a whole. The magnetic force cannot be discovered by means of a charged electric body at rest, since the magnetic force acts only between bodies when they both move relatively to the ether in the same direction. They must have an absolute motion through the ether. Relative motion is not sufficient. When one charged body moves through the ether while the other is at rest, no magnetic force is exerted between them. The ether, in the electron theory, is supposed to be absolutely at rest. It forms the standing ground from which all motion may be measured in absolute terms. There is, therefore, in the electron theory such a thing as absolute motion, and it is this that determines magnetic force. The greatest absolute motion with which we are brought into practical dealings is that of the earth round the sun, which is 3,000,000 cm. per second, or 19 miles per second. This is only $\frac{1}{10000}$th of the speed of light, so that two charged bodies placed at noon in a line at right angles to the sun's rays in the meridian plane

would only lose 0·01 per cent. of their attraction for each other, whereas they would not do so if placed east and west. The experiment may be tried some day, but the difficulties are very great, since the charge on a conductor is easily dissipated by the ions of the air, and the sources of error are considerable.

The fact that we can discover magnetic force, even if the electrons are moving with the small velocity of about 1 cm. per second, is due to the enormous quantities of electricity set in motion in a wire—quantities which we can never hope to obtain separately. Whatever magnetic force the electrons may exert owing to the earth's motion is compensated by the magnetic force exerted by the positive atoms, owing to the earth's motion. The one force exactly balances the other, and the only force remaining is that of the electrons relatively to the positive atoms—*i.e.* relatively to the wire itself.

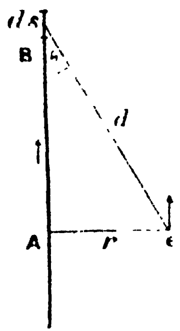

FIG. 21.

This is how it comes about that we may, for magnetic purposes, regard the ether as fixed to the earth, so long as we are not dealing with bodies possessing a free charge. The magnetic force between two moving electrons varies inversely as the

square of the distance. The magnetic force exerted by an infinitely long wire containing moving electrons upon an electron moving parallel to the wire is simply inversely as the distance. For let there be an electron at ϵ (Fig. 21), moving parallel to the wire A B, and let ds be a small portion of the wire. The magnetic force exerted upon ϵ is proportional to $\frac{\sin\theta}{d^2}$, since the electron is not moving along ds. The total force exerted by the portion of the wire above A in the direction of r is proportional to $\frac{i}{r}$, where i is the current and r the distance. A similar force is exerted by the wire below A, so that the total force is proportional to $\frac{2i}{r}$. The magnetic force round a wire, therefore, decreases simply as the distance increases. It may be measured by bringing another current i' within r centimetres of the wire. Then the force of attraction exerted upon 1 cm. of the wire carrying the current i' by the infinite wire carrying the current i is

$$\frac{2\,i\,i'}{r} \text{ dynes.}$$

If both i and i' are 10 ampères, and r is 1 centimetre, the force is 2 dynes. Hence a current equal to 10 ampères is called the "electromagnetic unit of current strength." It is ten times the practical unit, the ampère.

In practice it is impossible to realise either an

infinite wire or a current element. We must therefore find a more practical method of determining the ampère.

Take two wires, each 100 cm. long, and bend them into circles. Mount them facing each other in planes 1 cm. apart, and let them be traversed by a current of 1 ampère each. This can be secured either by inserting a small battery somewhere in each circle, or connecting them with a battery by means of a short break in the circle. If the two currents then go in the same direction, they will attract each other with a force of 2 dynes. If they go in opposite directions, they will repel each other with the same force.

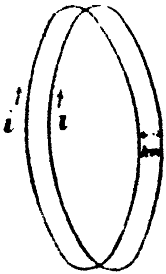

FIG. 22.

Hence we arrive at the following definition of the ampère, which is quite independent of magnets: –

An ampère is that current which, when traversing two circular conductors 1 m. in circumference in the same direction makes them attract each other with a force of 2 dynes when separated by a distance of 1 cm.

More generally, the attraction between two circuits is

$$\frac{2ci^2}{d}$$

where c is the circumference in metres, i the current

in ampères, and d the distance between the circles in centimetres.

We thus have two definitions of the ampère, one as the passage of 8·73 trillion electrons per second, which may be called the chemical definition, and the other as the current which exerts a certain magnetic force, this being the electromagnetic definition of the same quantity. Both definitions are consistent and identical; but of the two the chemical definition is the more fundamental. It should be remembered that currents can be measured with the greatest accuracy, not by their magnetic force, but by the passage of their electrons through a liquid, as in the electrolysis of silver nitrate or copper sulphate.

If the current were increased to such a pitch that the electrons travelled through the wire with the velocity of light, the attraction would be such that it would counterbalance the enormous repulsion exerted between the 138 armies of electrons in each circuit, which is masked by the presence of the positive atoms.

The fact that the force varies inversely as the distance shows that the two circuits will tend to approach each other with increasing force, and will ultimately coincide. When one circle is a little smaller than the other, the maximum attraction is at a distance equal to the difference of their radii.

In every case the magnetic force is at right angles

to the current. At any point in space the magnetic force may be measured in dynes by the maximum force experienced by 1 cm. length of a wire carrying unit current.

Thus the magnetic force at the centre of a circle due to a current passing through the circumference is

$$\frac{2\pi i}{r}.$$

This formula is the foundation of the measure of a current by means of a small magnet.

When a long cylinder is wound with wire carrying a current i, the magnetic force inside it is everywhere the same, and is equal to $4\pi n i$ where n is the number of turns per centimetre. Such a cylinder is called a solenoid. It forms an artificial magnet without iron.

The magnetic force due to a long wire carrying a current of one ampère is $\frac{1}{5}$ dyne at a distance of 1 cm. from it. The force is about the same as the earth's horizontal magnetic force. It is the force experienced by 1 cm. length of a wire carrying a current of 10 ampères when placed at a distance of 1 cm. from the first wire.

When two currents cross each other at an angle, they tend to coincide with each other and flow side by side in the same direction. Currents flowing from or towards the same point attract each other. If (Fig. 23, *a*) the current i were fixed and i' movable,

the latter would be pulled round in the direction of the arrows. If at the instant of crossing i the current i' could be reversed, it would be repelled and twisted round into the opposite direction. By reversing it at every crossing a continuous rotation could be produced, and a machine has been made to do this. If (Fig. 23, b) i' were only free to move at right angles

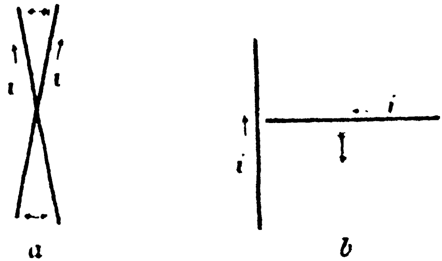

FIG. 23.

to itself, it would be urged in the direction of the arrow. If i is bent into a horizontal circle, and i' is movable along it, it will rotate continuously, as it does in a machine devised by Ampère.

We have dealt with the electrons moving in wires as the most practical cases of electro-dynamic attraction. But the attraction can also be observed with free electric charges. If a number of metallic knobs are mounted on an ebonite wheel and charged and the wheel is set rotating, the charges form a current of strength $n\,e\,v$, where e is the charge of each knob, expressed in "armies" or coulombs, n is the number of knobs, and v is their velocity. Thus

if there are 1000 knobs charged with 300 companies of electrons each (10^{-7} army), and the rim velocity is 100 cm. per second, the current is $100 \times 1000 \times 10^{-7}$, or $\frac{1}{100}$ ampère. Currents of this order have been obtained by Rowland by rotating a disc with charged sectors. Two such wheels or discs attract each other just as currents in wires would; but the attraction being of the order of a millionth of a gramme, is almost immeasurably small.

Electrons also influence each other when flying free, the magnetic force between them being proportional to their instantaneous velocities, and inversely proportional to the square of the distance between them. If they are moving in parallel lines but not abreast, the force must be multiplied by the sine of the angle between their direction of motion and the line joining them. If they are flying in different directions, the force must be multiplied by the cosine of the angle between their directions of motion.

The forces between moving electrons are thus perfectly determined. They consist of the electrostatic force, which may be regarded as invariable, and the electro-magnetic force, which depends upon their speed and direction. A clear grasp of the play of these two forces is the first essential step towards an understanding of electro-magnetic phenomena.

CHAPTER VIII

MAGNETISM

We saw in the last chapter that magnetic force is due to the steady motion of electrons or charged bodies generally; but that the magnetic force exerted by a metallic conductor carrying a current is due solely to the motion of the electrons which constitute that current. We saw, also, that magnetic force is only exerted on other moving electrons or moving charged bodies, but not on electrified bodies at rest.

I now intend to show that all magnetism consists in the steady motion of electrons in small orbits, and that all magnetic properties of bodies can be explained on this principle. By "magnetism" I mean that property whereby bodies exert magnetic force without any discoverable electric current traversing or surrounding them.

In broad outlines, the electron theory of magnetism is as follows: The atoms of all bodies are surrounded by several electrons describing orbits round them. like the planets round the sun. When these orbits are nearly in the same plane, as in the Solar System, the bodies are "magnetic," or rather "paramagnetic," like oxygen and aluminium. When, in addition, the

orbits are large enough to influence each other across the average distance separating the atoms, the bodies are "ferromagnetic," like iron, cobalt, and nickel. When, on the other hand, the orbits of the electrons revolving round the same atom lie in various planes, the bodies are not paramagnetic. They are usually described as "diamagnetic." But in reality *all* bodies are diamagnetic, and paramagnetism is a special property which masks the inherent diamagnetism of the bodies. A permanent magnet is a paramagnetic body in which the orbits of the majority of the electrons lie in parallel planes, with the revolutions in the same sense, and this parallelism is maintained by the mutual attraction of the orbits.

Such, in short, are the main principles of magnetism according to the new theory, which owes its successful application to magnetism chiefly to Prof. Langevin, of Paris.

There is no "magnetic fluid," no "free magnetism," no "magnetic pole." In the electron theory, magnetism as a distinct entity disappears, being resolved into the steady motion of electrons. Thus passes a conception which has given rise to more misunderstandings and false speculations than perhaps any other in the history of science.

I explained (p. 156) that an artificial magnet without iron may be constructed by coiling a wire on a cylinder, and sending a current through it. If the current in the wire is one electro-magnetic unit (= 10

ampères), and these are n turns for every centimetre length of the cylinder, the magnetic force at the centre of the coil is $4 \pi n$ dynes. In other words, if i is the current and n the number of turns, the total current circulating round each centimetre length of the solenoid is $n i$. This total current per unit length we will denote by I electro-magnet units or 10 I ampères. *It is identical with what is known as the intensity of magnetisation I.*

A body has unit intensity of magnetisation if a total current of 10 ampères circulates round unit length of it, the length being reckoned in the direction of the magnetic axis.

We will now proceed to explain how a permanent magnet may be regarded as a body round which an electron current is steadily circulating.

The idea that a magnet is made up of innumerable smaller magnets of molecular dimensions is some eighty years old. It was put forward by Ampère to explain the fact that however much a magnet is broken up, each fragment is a complete magnet. Knowing that an electric current attracts or repels another, according to its direction, he assumed that each molecule of a magnetic substance was surrounded by an electric current. Still, regarding electricity as an imponderable fluid, he was unable to say what constituted that mysterious molecular current. No further light was shed on this matter until the advent of the electron theory, although the

conception of molecular currents was applied with much success to magnetic phenomena by Weber, and later by Ewing.

Ampère furnished an ingenious and successful explanation of how a large number of small molecular currents could make up a large magnet.

If the molecules were square in section and packed close together, and each molecule had a current circulating round it in the direction of the hands of a watch, then a small section across a magnetic needle, greatly magnified, might be represented by the diagram (Fig. 24). Wherever two molecules join, there are two currents in opposite directions, which, of course, neutralise each other. It is only the currents on the free sides of the molecules that exert any magnetic effect outside the magnet. The net effect is, therefore, as if a current equal to the molecular current circulated round the outline of the section. It is obvious that, whatever section is taken, whether including a large or small number of molecules, the current round the outline is always the same, being equal to the molecular current, which is invariable.

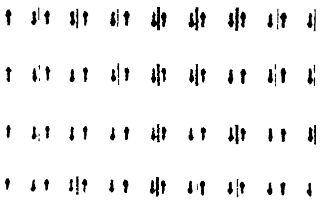

Fig. 24.

For Ampère's mysterious molecular currents, let

us now substitute revolving electrons, or, rather, let us define the molecular current as a convection of electricity in the shape of electrons revolving round each positive atom.

The above reasoning remains substantially the same. True, the electrons do not describe square paths; but the error introduced by regarding their paths as square is not great, and the convenience of calculation is considerably enhanced. As before, it is only the electrons circulating in the outline that count for external magnetic effect, and the current round the section is equal to the molecular current, which, in ampères, is equal to the number of armies of electrons passing any point of the outline in one second.

This theory can be tested quantitatively as follows The calculation is only roughly approximate; but although several of the data are uncertain, it shows that the electron theory of magnetism leads to no absurdities when reduced to figures.

A cubic centimetre of iron is supposed, with good reason, to contain about 10^{24} (one quadrillion) atoms. If there are 10^{8} atoms ranged along one edge of the cube, the total number in the cube will be 10^{24}. Let each atom have one electron revolving round it, and let all the circuits face one of the sides of the cube. Then an electron current will circulate round the four adjacent sides. The molecular current, reckoned in electrons per second, is measured by the number

of revolutions per second of the electron round its atom. This, as estimated on p. 32, is $2{\cdot}2 \times 10^{15}$. Multiplying this number by 10^8, the number of atoms along one edge, we get for the total electron current circulating round the cube (in other words, for its "intensity of magnetisation") the figure

$$2{\cdot}2 \times 10^{15} \times 10^{8} = 2{\cdot}2 \times 10^{23}$$

electrons per second. Since one ampère is a current of $8{\cdot}79 \times 10^{18}$ electrons per second, the above current in ampères is

$$\frac{2{\cdot}2 \times 10^{23}}{8{\cdot}79 \times 10^{18}} = 25{,}100 \text{ ampères.}$$

It seems incredible that an enormous current like that should circulate round a bit of iron the thickness of one's finger without making it burst into flame. But, then, we must remember that the current does not heat a wire because electrons move in it, but because their motion, acquired under electric force, is stopped by collision every now and then. In magnetic metals the electrons are free to revolve, and in doing so they spend very little energy.

The greatest intensity of magnetisation hitherto actually observed is 1700 units, meaning that a current of 17,000 ampères circulates round each centimetre length of a bar of iron magnetised to saturation. The agreement between these two figures — viz.

25,100 ampères for absolute theoretical saturation, and 17,000 for the highest saturation practically attained—is remarkably good. But too much importance should not be attached to it. The calculation is only intended to show that the electron theory accounts for magnetism quantitatively as well as qualitatively. To calculate the magnetisation of different substances we shall have to know more about the number of revolving electrons per atom, the speed of revolution, and the size of their orbit.

I have supposed in the above calculation that only one electron revolves round each atom. This is on a par with the observation that every atom is only capable of losing one or two, or at most not more than three, electrons. But it does not follow that the atom only contains from one to three electrons. The modern view is that the mass of the atom contains a large number of electrons, bound together by some hitherto mysterious body of positive electricity. Thomson supposes that these electrons revolve within the positive body, and are influenced by magnetic forces. They probably circulate in all sorts of planes, thus making up a diamagnetic atom in the ordinary sense. The detachable electron probably revolves at a greater distance, somewhat like Neptune or the comets in the Solar System, and it owes its predominant magnetic effect to its large orbit. As we shall see,

two orbits influence each other in proportion to their areas. In ferromagnetic bodies like iron, a few electrons must possess exceptionally large orbits. In soft, unmagnetised iron these orbits face every way, or are bound up together in small groups. When the soft iron is brought into a field of magnetic force, the orbits, or what we may call the molecular currents, are drawn round till their own magnetic fields coincide with the external field. The iron is then "magnetised." Needless to say, the addition of all the molecular fields to the external field greatly strengthens the original field. It would require very exceptional contrivances to make a current of 25,000 ampères circulate round a narrow tube. It is quite impossible with purely electrical means to get such a current to circulate within a space of a cubic centimetre. But by calling in the aid of the molecular currents—ready-made currents, which only require "turning on"—we obtain the powerful magnetic fields with which the electro-magnet is associated.

When the external magnetic field is removed, it may happen that most of the molecular currents remain in their new positions, being held there by their mutual attractions. In that case we have what is called "residual magnetism." In soft iron this residual magnetism amounts to about 80 per cent. of the magnetism induced in fairly strong fields. But the slightest tap or other mechanical

disturbance makes the molecular currents swing back into their higgledy-piggledy state. In steel, on the other hand, the residual magnetism is held even when the field is reversed until the field acquires a considerable strength. This indicates that in steel the orbits are so large, or so close together, that when they are once in line a considerable force is required to turn them into other positions.

This brings us to the consideration of magnetic "moments." The turning couple experienced by a molecular current, or any other electric current in a magnetic field, is proportional to its magnetic moment. This moment is made up of two factors, one of them being the strength of the current, and the other the area round which it circulates. If the strength of a molecular current is 10 ampères, and its area is 1 sq. centimetre, it experiences in a unit magnetic field a maximum couple of 1 dyne-cm. Generally, a circuit of area A, and current strength i, has a moment $= Ai$.

If the current in a solenoid is I electro-magnetic units per cm. length, its sectional area A sq. cm., and its length l, then its magnetic moment is IAl. The product IA or (current per unit length) (sectional area) is called the "pole strength" of the solenoid or other magnet. The name is justified by the fact that, as far as the external force of the magnet is concerned, it may be ascribed to two centres, situated

at or near the two free ends of the magnet, and of a "strength" equal to the product of the magnetic intensity into the area. But these poles are mere mathematical fictions of a high degree of artificiality. When the bar is twisted into a complete circle, the poles disappear, although the molecular currents remain nearly the same as before.

The magnetic moment of a bar magnet of length l and pole-strength IA is IAl. Or if m is put for the pole-strength IA, the moment is ml. Hence the moment of a bar magnet may be measured by multiplying its pole-strength by its length. A unit magnetic pole is possessed by a bar whose sectional area multiplied by the total current circulating round it per unit length is unity. Thus, *if the molecular currents circulating round a bar of 1 sq. cm. section amount to 10 ampères per cm. length, that bar has unit magnetic poles.* If it is 1 cm. long it has unit magnetic moment.

The magnetic moment determines the magnetic force exerted by a magnetic circuit or a solenoid at any point far away from it in comparison with its length. If any such point is chosen at random, the force increases in direct proportion to the moment. Thus, the force exerted by a small bar magnet or magnetic needle may be doubled by doubling either its length or its pole-strength. The force exerted by a molecular current or other small plane circuit may be doubled by doubling either

the current or the area. In both cases the process is essentially the same. In the bar magnet the current can only be doubled by doubling the length, since the molecular currents cannot be altered. The pole-strength can be doubled by doubling either I or A. If steel bars are used, I is limited by a certain maximum (17,000 ampères per cm. length), and the pole-strength can only be doubled by doubling the area, as in the case of the circuit. The analogy between circuits and magnets is, therefore, very far-reaching. The differences between them are due to the great strength of the molecular currents. This great strength, while offering many advantages, suffers under the drawback that the molecular currents easily fall out of alignment, thus leading to demagnetisation. The solenoid or other artificial magnet is much feebler than the magnet containing iron, but more reliable than the permanent magnet. The best and strongest magnets are made up by combining both forms, thus offering the certainty of the solenoid and the strength of the iron magnet. Such combinations, constructed by winding a current-bearing wire in many turns round a soft iron core, are well known under the name of electro-magnets.

To make the analogy between magnets and solenoids more clear, it is necessary to go a little further into the nature of a magnet pole. The conception of poles, though misleading in many ways, has also

had its uses. It has furnished a convenient abbreviation for many physical terms, and has served to give us some idea of the action of a magnetic field upon a magnetic needle. But when that conception was strained in order to account for the nature of magnetism, it not only failed, but retarded actual progress in that direction for generations.

The magnetic action of a long and thin solenoid, like that of a long and thin magnet, may be sup-

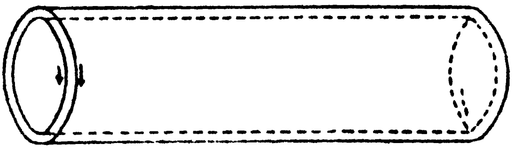

FIG. 25.

posed to be concentrated at two points very near the ends, which are called its poles. But every turn of the solenoid, like every section of the magnet, exerts its magnetic force *quite independently* of any other turn or section. Its action is not abolished or "neutralised" by that of any other part. It persists intact, and if a turn in the centre of a solenoid appears neutral, it is only because we are not using the proper means of demonstrating its magnetic action.

That the action appears to be concentrated at the poles is, so to speak, an illusion, due to the peculiar way in which the actions of the individual turns sum themselves up.

Consider two solenoids of equal length, but different thicknesses (Fig. 25), placed one inside the other. The electron currents, when looked at from the left-hand end, all appear to revolve in the direction of the hands of a watch. They therefore all attract each other, and since they are already as close together as they can be, they will not alter their relative position if they are free to move. In other words, there is no resultant force upon them;

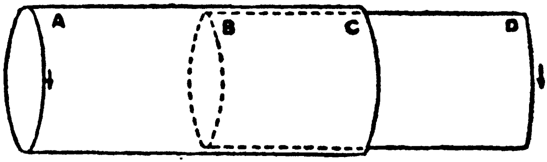

FIG. 26.

they are in a position of equilibrium. Now let the smaller solenoid be pulled part of the way out of the larger one (Fig. 26). Then the two portions between B and C are in equilibrium with respect to each other as before; but the portions A B and C D are not. The portion A B attracts every turn in the smaller solenoid. The attraction is proportional to the moment of each turn of the larger solenoid, and inversely proportional to the cube of its distance. On the other hand, the attraction is directly proportional to the number of turns between A and B. If A B = l, we therefore have the attraction proportional to $\frac{1}{l^3}$, and also to l itself. The

result is that it is proportional to $\frac{l}{l^3}$, or $1/l^2$. It is inversely as the square of the distance.

The above reasoning supposes that the length of the solenoids is great in comparison with their diameters. This provision need not disturb us, since without it we cannot speak of poles at all, even in bar magnets.

If one of the solenoids is reversed, the attraction will be converted into a repulsion, and the smaller one will be expelled from the larger one. If, however, the two solenoids are laid alongside each other in the same direction, currents proceeding in the same direction will be adjacent to each other, and will attract each other. If the solenoids are placed side by side, but not end to end, they will tend to move so as to bring their ends together, in order to have the attracting currents as close together and as numerous as possible. Here, again, we have the illusion of polar action. But since the currents have only one point in contact, the attraction is much feebler than when one solenoid is inside the other.

The inverse square law may be deduced from a general principle of the integral calculus. This principle, which is capable of many useful applications, is as follows: When a force exerted by an infinite line upon a point outside it varies as the nth power of the distance between the point and an element of the line, the total force exerted by

the infinite line varies as the $(n+1)$th power of the distance between the point and the line. Thus, if the point is an electron and the line is a line of electrons, the repulsion between the electron and each element of the line varies inversely as the square of the distance—*i.e.* as the (-2)th power of the distance. Hence the total repulsion varies as the (-1)th power of the distance—*i.e.* inversely as the distance.

The magnetic force exerted by a small circuit varies inversely as the cube of the distance. Hence the magnetic force exerted by an infinite line threaded with such circuits varies inversely as the square of the distance. Since, in the case of a circuit placed outside an infinite solenoid, the force is parallel to the solenoid itself, and equal in both directions, the two halves of an infinite solenoid will compensate each other, and the resultant force will be zero. But if the solenoid is infinite in one direction only, a resultant force will appear, which is inversely proportional to the square of the distance from the end. This force will be apparently due to the existence of the end. It will be greatest at the end, and will appear to be concentrated there. In short, the illusion of the magnetic "pole" is complete.

Let this end be dipped into iron filings. It will magnetise some of them, and enable them to adhere to each other. The adhesion will be strongest where the molecular circuits can place themselves in paral-

lelism with the solenoid circuits, so as to form whirls of molecular currents proceeding from the end of the solenoid. The solenoid has "poles" just as a bar magnet has, neither more nor less.

The pole-strength is unity, as shown above, when the product of the sectional area of the solenoid into the total current carried per cm.-length is unity. If the sectional area is one square millimetre, the current per cm.-length must be 100 electro-magnetic units, or 1000 ampères, since 1 sq. cm. = 100 sq. mm. The pole of the solenoid is then a unit pole. The pole of a magnet of the same section, with a molecular current of 1000 ampères circulating round it per cm.-length, is also a unit pole. Both unit poles have an important property. *A unit magnetic pole, placed at a distance of 1 cm. in air from another unit pole of the same sign, repels it with the force of one dyne.*

This is the law upon which the "electro-magnetic" system of units has been based. The "electrostatic" system, on the other hand, is based upon the inverse-square law governing the forces between quantities of electricity. The establishment of two different systems of units was unavoidable before magnetism had been reduced to electrical principles. But it was unfortunate, and it considerably increased the difficulties of the learner. The whole of the magnetic and electric units can now be reduced to terms of electric quantity. The volt, ampère, ohm, cou-

lomb, and other practical units are retained intact; but instead of basing them upon a mathematical abstraction like a magnetic pole, they will be interpreted in terms of Nature's own unit of electricity, the electron.

CHAPTER IX

INDUCED CURRENTS

WE have hitherto only considered steady currents, which, in metals, are constituted by the motion of electrons only, with a constant average velocity. This motion takes place in a direction opposite to what was hitherto described as the direction of "the current," and gives rise to a magnetic force in the surrounding space, which is proportional to the momentum of the electrons.

We have next to consider the case where electrons are started or stopped—in other words, where the current varies.

Now, we know that all electrons in a wire are constantly being stopped by collision with neutral atoms, and started again along the electric field of force as soon as they are liberated. But these startings and stoppages make no difference to the external magnetic action, since they are so exceedingly numerous, and all stages in the process are represented at any given instant. On the whole, the external effect is just as if the electrons were moving with a steady speed through the wire. The only indication we have of the actual collisions is the heat developed in the

wire, which represents the energy of motion transformed into heat when the electron is stopped. But what happens when all the electrons are stopped at the same instant?

What does happen is very much like what happens when any larger body is stopped. The energy of motion is transformed into some other form of energy, and is eventually radiated out into space in the form of heat or other ether waves.

The kinetic energy or energy of motion of a ponderable body is equal to half the product of its mass into the square of its velocity = $\frac{1}{2}\, m\, v^2$. Thus, the kinetic energy of one gramme moving with a velocity of 1 cm. per second is $\frac{1}{2}$ erg. In other words, by stopping it we may make it perform half an erg of work. It also takes half an erg of work to impart to the gramme a velocity of 1 cm. per second. This amount of work is done whenever we exert a force of 1 dyne over a distance of $\frac{1}{2}$ cm.

On this principle, let us calculate the energy of motion of an electron. Its mass is taken to be $0{\cdot}6 \times 10^{-27}$ gramme (see p. 23). Its velocity can never exceed that of light, which is 3×10^{10} cm. per second. Hence, the kinetic energy of the electron can never be greater than $\frac{1}{2} \times 0{\cdot}6 \times 10^{-27} \times 3^2 \times 10^{20}$ or $2{\cdot}7 \times 10^{-7}$ erg. Similarly, the kinetic energy of a "company" (one electrostatic unit) of electrons is always less than 800 ergs, and the kinetic energy

of one coulomb, or "army," of electrons is always less than 2·38 billion ergs.

The amount of energy required for imparting a given velocity to an electron is, however, affected by a magnetic field. That this must be so is evident from the principle of the conservation of energy. When an electron moves parallel to a current-bearing wire in the same direction as the electrons in the wire, it is attracted towards the wire. In other words, it possesses an energy of position (or potential energy) in addition to its own energy of motion. This energy of position is directly proportional to the velocity of the electron, since the attraction between it and the wire is directly proportional to that velocity. It is also proportional to the momentum of the electrons in the wire—in other words, to the magnetic field generated by them.

It is, therefore, more difficult to start an electron in the same direction as other moving electrons than to start it in empty space. It requires more energy, more expenditure of work. The excess is directly proportional to the magnetic field created by the electrons in the wire, or simply to the magnetic field, *howsoever created.*

Matters can be set right by imparting an extra amount of momentum to the electron in proportion to the magnetic field. This momentum may be imparted to it by bringing a force to bear upon it for a definite time. Now, a force acting for a certain time

produces what is called an "impulse." A force of one dyne acting for one second produces an impulse of one dyne-second. If it acts upon one gramme, it produces in it a velocity of one centimetre per second. Acting on a kilogramme, it produces a velocity of $\frac{1}{1000}$ cm. per second. Acting upon a milligramme, it imparts to it a velocity of 10 metres per second. In every case, the same impulse produces the same momentum.

In order, therefore, to start an electron through a magnetic field, an extra impulse has to be given to it in proportion to the strength of the magnetic field. Now, if the electron is already in motion, and a current is suddenly sent through a neighbouring wire, a magnetic field will be created round the electron. If it fails to receive the necessary extra impulse, the impulse will be deducted from its own velocity. The debt has to be paid somehow.

If, instead of a single electron, there is a crowd of them moving in another wire, the state of things will be the same. When the magnetic field is started, they all receive a set-back. Their velocity is reduced by a certain amount proportional to the magnetic field.

If the magnetic field is reversed, the impulse is also reversed, and instead of a retardation the electrons receive an acceleration of the same amount. In both cases the impulse is in the direction opposite to that of the current in the wire, and proportional to that current.

This is the principle of electro-magnetic induction, or the production of currents by changes in other currents.

The fundamental phenomena of induced currents were discovered by Faraday, and formulated by him in the language of "lines of force." I have so far avoided this expression in order to concentrate attention upon the events happening within the conducting wire. I shall now introduce it, but with the restrictions and limitations imposed by the new atomic theory of electricity.

When a sheet of paper is laid over a bar magnet and dusted with iron filings, the filings arrange themselves in curved lines, which approximately represent the direction in which a free magnetic pole would travel if placed in the magnetic field. These lines are called "lines of force," because the tangent at any point of one of the curves represents the direction in which the resultant magnetic force would urge the free magnetic pole.

Now, Faraday imagined that all space round a magnet is filled with some invisible lines corresponding in direction to these lines of iron filings. To these ethereal lines he ascribed a physical reality and physical properties, such as a tension along them and a pressure at right angles to them. He was thus enabled to "explain" a variety of magnetic phenomena, or, rather, to summarise them in the light of his fundamental assumption of physical lines of force.

It cannot be denied that the conception of lines of force has been of great practical utility. It has enabled engineers to visualise the happenings in a magnetic field. In the hands of Maxwell and his brilliant successor at Cambridge, the method of lines and tubes of force has been used to describe and measure magnetic phenomena with marked success; but, so far, all attempts to demonstrate their real existence in the ether have utterly failed. The very fact that a unit magnetic field can be *arbitrarily defined* as containing a certain number of lines per square centimetre implies that these lines have no real existence.

Within a permanent magnet there is very little doubt that the molecular currents are mostly arranged in rows with their axes in the same line, thus forming magnetic filaments, or elementary solenoids. These, at all events, really exist. They number about 10^{16} per square cm. of cross-section, and that number measures the intensity of magnetisation. The lines of force that are supposed to continue them outside the magnet may be used to measure the magnetic force at any point outside. It is simply equal to the number of lines vertically cutting unit area at that point. A unit-magnet pole is defined as a pole emitting 4π lines of force, so that there is one line passing through every sq. cm. of a sphere of 1 cm. radius described about it. This definition at once shows the purely arbitrary char-

actor of the assumptions made; but it enables us to state the law of electro-magnetic induction in a terse manner, as follows:—

The impulse of electro-magnetic induction produced by the creation or destruction of a magnetic field is at right angles to the lines of force, and proportional to their density. When their density is changed it is proportional to the difference of density.

It does not matter how the field is made to vary, whether by moving the current-bearing wire, varying the current, or moving a permanent magnet. The impulse of induction is proportional to the change in the field—*i.e.* the change of density and direction of the lines of force.

The simplest cases to investigate are those in which the magnetic field is uniform. We have seen above (p. 156) that the field inside a long solenoid is $4\pi n i$ units, where i is the current through the wire, and n the number of turns per cm. This field is nearly the same at any point within the solenoid, and is independent of its diameter. We will, therefore, operate with a large solenoid 10 cm. in diameter, having ten turns to the centimetre length, bearing a current of 10 ampères, and having a total length of 1 metre. The magnetic force inside it will then be $4\pi \times 10 \times 1$, since 10 ampères are just one electro-magnetic unit of current. The magnetic force inside will be 126 units, or about

600 times the earth's horizontal magnetic force in our latitudes. In the language of the "lines of force," there will be 126 lines of force penetrating every square cm. placed across the axis of the solenoid. The total number of lines of force through the solenoids will be 126 × its area. The radius being 5 cm., its area is 25π, or 78·4 sq. cm. Hence the total "lines" passing through its interior amount to 9880.

Let a small circle of wire of radius 1 cm. be placed within the solenoid, with its plane at right angles to the axis of the solenoid. Its area will then be 3·1416 sq. cm., and the number of lines of force passing through it will be $3{\cdot}1416 \times 126 = 396$.

When the current in the solenoid is broken, its magnetic field is suppressed. The electrons in the circle of wire thereupon experience a force tending to make them circulate in the same direction as the former current in the solenoid. It is just as if part of the momentum of the electrons in the solenoid had been transferred to those in the circle. Now, the rate of transfer of this momentum will vary, of course, with the rate of stoppage of the original current—*i.e.* with the rate of change in the magnetic field. The amount of momentum transferred varies with the extent to which the magnetic field created by the solenoid is covered. If matters were reversed, and the circle bore the original current, the solenoid would receive the whole of its electric momentum on stoppage of the

current. But, as it is, the circle will only receive a portion which is proportional to its area, and the rate at which it receives it measures the electromotive force "induced" in the circle.

We have thus arrived at these two important principles:—

1. The induced E.M.F. is proportional to the rate of change of the magnetic field.

2. In a uniform field, the induced E.M.F. is proportional to the area of the circuit into which it is induced.

Faraday's conception of lines of force enables us to combine these two principles into a single rule, worded as follows:—

The E.M.F. induced in a circuit by a change of magnetic field intensity is proportional to the number of lines of force added to, or withdrawn from, its area in the unit of time.

Thus the starting or suppression of the 369 lines of force passing through the area of the circle within one second will induce in the circle an E.M.F. of one 396 units. These units, it should be stated, are not the volt or practical unit, but the electro-magnetic unit of 10^{-8} volts. The E.M.F. will, therefore, be very feeble, and, indeed, all but undiscoverable. But it can be increased by shortening the time during which the change in the field takes place. If the current were broken in a millionth of a second, the E.M.F. would be 3·96

volts. If, instead of one circle of wire, there was a short coil of 10 turns, the E.M.F. would be 39·6 volts.

The *current* through the circle of iron depends not only upon the induced E.M.F., but also upon the resistance of the wire. If the induced E.M.F. is 3·96 volts, and the resistance 0·001 ohm, the current strength will be 3960 ampères. But this current will only last as long as the E.M.F. lasts—*i.e.* for one-millionth of a second. Hence the *quantity of electricity* passing any section of the wire circle is not 3960 coulombs, but 0·00396 coulombs. But this quantity is quite independent of the rate of change in the magnetic field. A slow rate of change means a small E.M.F., but a current more lasting in proportion. Hence we get the simple rule: The quantity of electricity passing any section of a conductor is proportional to the change in the number of magnetic lines of force passing through the area of the circuit.

The "number of lines of force passing through an area" is called the "magnetic flux" through that area. Hence the quantity of electricity passing is measured by the change in the magnetic flux through the circuit. As long as the magnetic flux goes on changing the electricity passes through the circuit, and its speed depends upon the rate at which the magnetic force changes. Its direction is determined by the direction of the magnetic field.

The direction of a magnetic field is determined by

reference to the earth. The body of the earth is itself a magnet, and it has a north and a south magnetic pole. Every permanent magnet has also two poles, and much confusion has been occasioned by the various methods of naming them. When it was known that unlike poles attract each other it was thought to be most logical to call that end of the magnetic needle which points towards the north its south pole, and the south-seeking end its north pole. But popular usage adhered to the practice of calling the northernmost pole the north pole, and *vice versâ*. This practice is even now adhered to on the Continent. The best way out of the difficulty is that suggested, I believe, by Silvanus Thompson, who calls the north end of the needle the north-seeking pole and the south end the south-seeking pole. This is clear and precise. But all these ambiguities are avoided if we refer all definitions to the motion of electrons. If a zinc and copper couple are floated in dilute sulphuric acid, and the wire joining them is turned into a coil, that coil turns its plane in a direction at right angles to the magnetic meridian and in such a manner that the zinc is towards the east and the copper towards the west. This means that the electrons in the upper wire flow in the direction of the sun's motion in the heavens, and in the lower half of the coil they flow from west to east. Hence the electron current in the earth's surface also flows from west to east, or contrary to the sun's

apparent motion. It flows, in fact, in the direction of the earth's revolution. Now, it has been proved that the mere rotation of a negatively charged sphere about its axis generates a magnetic field at its surface, and it might be supposed that that is the origin of the earth's magnetism; but a simple calculation, on the basis of the earth's high electrical potential, shows that the earth's motion is only capable of accounting for about one ten-thousandth part of the actual magnetic field. The actual field appears to be due partly to discharges from and into interstellar space, and partly to thermo-electric effects. It is known that, when a point in an iron wire is heated, and the slope of temperature is steeper on one side than on the other, there is an electron current from the steeper to the less steep side. Now, such a difference of steepness is actually observed in the case of the earth. The rise of temperature in the morning is more rapid than its fall in the afternoon. The point of maximum temperature is under a meridian about 30° east of the sun's position, and there is a steep temperature gradient towards the west, and a flatter gradient towards the east. If the earth behaves like iron in this respect—and iron is one of the commonest constituents, not only of the earth, but of other heavenly bodies—we should expect an electron current to pass from west to east. This would explain the larger part of the earth's magnetism; but, of course, nobody can claim that it gives

a complete explanation until we can test it with some quantitative rigidity. In any case, it is useful to remember that the electron current round the earth proceeds from west to east, counter-sunwise (Fig. 27). In a magnetic needle, M, the electron current runs so that on its side nearest the ground the electrons run in the same direction as they do in the ground. Whenever, therefore, a north-seeking pole of a needle points towards us, we know that the electron current revolves round it in the direction of the hands of a watch. And when the end of a solenoid points towards us, and the electron current, on its way from the zinc to the copper, passes round it clockwise, we know that that solenoid, suspended or floated freely, will point the same end towards the north. A smaller solenoid within it will have a current in the same direction induced in it when the main current is broken, and a current in the opposite direction when the main current is started again.

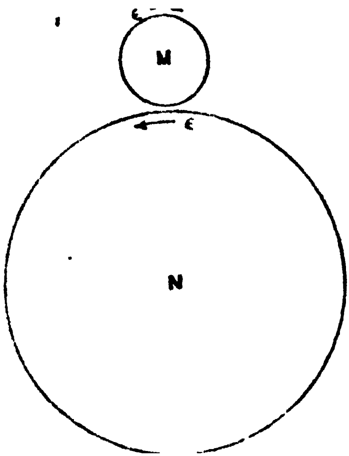

FIG. 27.

Since the electron current in the wire consists of a

vast number of moving electrons, it may be regarded as a bundle of innumerable conductors of very small diameter, and it is evident that these will influence each other. It will be more difficult to start a current in a thick wire than to start the same aggregate current in a number of thin wires taken separately. The phenomenon whereby a current in a wire hinders its own increase or decrease is called self-induction. It is measured by the "coefficient of self-induction," or, shortly, the "inductance," and is numerically equal to the magnetic flux through the circuit when unit current flows through it. In a long straight solenoid traversed by unit current (10 ampères), the magnetic force is $4\pi n$, where n is the number of turns per unit length. If A is the area of the section, the number of lines of force passing through each turn is $4\pi n A$; and since there are n turns per unit length, the number of lines is $4\pi n^2 A$, so that the inductance of a solenoid of length l is $4\pi n^2 l A$. This is equal to twice the energy in the magnetic field due to unit current.

The inductance may be enormously increased by putting an iron core into the solenoid, as in that case the lines of force due to the molecular currents are added to those of the solenoid.

CHAPTER X

RADIATION

HITHERTO we have considered electric actions without reference to the time taken in transmitting them from one place to another. We have dealt with them as we would with the phenomena of gravitation. It is known from astronomical observations that gravitational force is transmitted through space with a practically infinite velocity, a velocity so great that we cannot discover any time interval elapsing between the establishment of a given configuration of gravitating masses and the action of the gravitational force predicted by Newton's law. If, for instance, gravitation were transmitted through space with the velocity of light, there would be a certain retardation or lag of the force between two celestial bodies behind their geometrical positions. If a body were falling towards the sun and were crossing the earth's orbit, the force exerted by the sun upon it at every instant would not be the force due to its position at that instant, but would be the force due to the position it occupied eight minutes before that instant, since the gravitational force would take eight minutes to traverse the distance

between the sun and the earth's orbit. Such a lag would upset all calculations based upon Newton's simple law of attraction, and could not fail to be discovered.

It was thought for a long time that electric and magnetic forces were propagated instantaneously throughout observable space, or, at least, with the speed of gravitational force. In that case a magnetic field produced by exciting an electromagnet would no sooner be established in our laboratories than its influence would extend to the sun and the fixed stars. Likewise, if we could suddenly create or destroy a lump of matter, an increase or diminution of gravitational force would be instantly felt throughout the universe.

If a magnetic-field were to oscillate between a maximum and a minimum value, its influence at any point outside oscillates at the same rate: but the distance between two successive maxima of influence depends upon the rate of its propagation. With an infinite speed, the "wave-length" or distance between successive maxima would be infinite. If we had any means of creating or destroying matter, we could produce gravitational waves of infinite wave-length. But the science of optics has made us familiar with a velocity of propagation which, though very large, is still quite measurable. It is the velocity of light, which is 3×10^{10} cm. per second, or 186,000 miles per second, and the experiments of

Hertz have proved that a magnetic field is propagated outwards with that velocity. This means that when a magnet is made and unmade, waves of magnetic force travel out into space with a wave-length proportional to the time elapsing between two successive makes or breaks. If a break occurs every eight minutes, the wave-length is equal to the distance of the earth from the sun. If it occurs a million times per second, the wave-length is about one-sixth of a mile.

There is thus a close analogy between the propagation of light and the propagation of magnetic force. Both processes may be classed under the word "radiation," which may be defined as a process in which a disturbance is propagated through space without the intervention of ponderable matter. Light-rays, heat-rays, and rays of magnetic force come under this heading. Cathode rays do not, since they are simply projected electrons, nor canal rays, since they are projected positive atoms.

We have in the previous chapters become familiar with three electric actions at a distance: (1) Electro-static force, or the force between charged bodies at rest. (2) Magnetic force, or the force between charged bodies in steady motion. (3) Inductive force, or the force between charged bodies under acceleration.

The second and third of these forces do not come into play until electric charges—*i.e.* electrons or

positive atoms—are moved. Since we can produce such motion at will, we can determine the velocity of propagation of these forces by the methods employed in determining the velocity of light without the aid of heavenly bodies, or by somewhat similar methods. But we cannot either create or destroy an electric charge. Electricity is not a mode of motion. It is as indestructible as matter itself. Hence we cannot determine the velocity of propagation of electrostatic force by purely terrestrial experiments. If we knew the exact value of the electric charges of the planets, there would be a faint chance of discovering a finite rate of propagation of the electrostatic force between them; but we have already seen (p. 70) that that force is insignificant in comparison with the gravitational force between them.

We cannot, therefore, say anything about the rate at which electrostatic force is propagated. Like that of the other static force, gravitation, it may be infinite; and we have as much right to speak about electrostatic rays or waves as we have to speak of rays or waves of gravitational force.

But the rate at which the dynamic forces (2) and (3) are propagated is well known. They are propagated through space with the velocity of light, and if any matter containing free electrons or positive atoms intervenes, their rate of propagation is lessened, just as the velocity of light is diminished under the same circumstances.

Consider two parallel wires of infinite length, along which electron currents move in the same direction. There is a magnetic attraction between them which remains constant as long as the currents remain the same. There is no electrostatic force, and no inductive force between them. The magnetic force being steady, there are no magnetic waves, no magnetic radiation. But let the current in one wire, which we will call A, diminish steadily to zero, then the magnetic field will also decrease steadily to zero, and the magnetic force between the wires will vanish. It is interesting to note the precise manner in which the magnetic force vanishes. The magnetic force is conditional upon the existence of two magnetic fields, each due to an electron current.

When the current in A falls to zero, the magnetic field of A vanishes at the same instant. But only at the wire itself. It takes some time to vanish in regions some distance away from the wire. At B it only vanishes after an interval of time, which depends upon the distance between A and B. If that distance is 186,000 miles, then the magnetic force on B persists for one second after the current in A has ceased to flow. The decrease of magnetic force in A thus produces a pulse of demagnetisation extending into infinite space with the velocity of light. This pulse is accompanied by a pulse of inductive force. As we have seen in the last chapter, an acceleration or retardation of electrons in a wire

produces a displacement of electrons in the opposite direction in a neighbouring wire, the displacement of electrons across any section of the wire being proportional to the change in the strength of the magnetic field. We have, therefore, two different effects produced in B when the current in A diminishes to zero.

(*a*) The magnetic force between A and B diminishes as the current in A diminishes.

(*b*) The electrons in B undergo an inductive acceleration in the direction of the main current while the decrease in A continues.

In (*a*) we have, therefore, a steady diminution of a force acting in the line joining A and B. In (*b*) we have a steady force acting at right angles to the line joining A and B, and lasting only as long as the current in A is undergoing a change. The forces (*a*) and (*b*) are in the plane of the two wires, but are at right angles to each other.

Now, the force (*a*) is a "magnetic" force, and is, by the older methods, measured as the force upon a magnetic "pole." But the magnetic lines of force are supposed to mark out the lines along which a "free magnetic pole" would travel. There is no such thing as a free magnetic pole; but if there were, it would revolve round and round a current-bearing wire. The magnetic lines of force will therefore cut the plane containing the wires A and B at right angles. Hence it is usual to say that the

magnetic force is always at right angles to the "electric" (inductive) force, and both are in the plane of the wave front—*i.e.* in the plane normal to the direction of propagation. Since in the modern theory all magnetic forces are resolved into forces on moving electrons, the magnetic force acts in the direction of propagation of the wave. It is a "longitudinal" force, while the inductive force is a "transverse" force, and only the latter is in the plane of the wave-front.

These considerations lead up to the important conception of an *electro-magnetic wave*. Since no magnetic wave can be created without changing the magnetic force and thus producing an inductive pulse, and since no induction is possible without moving electrons and (therefore) magnetic fields, it follows that in all electro-magnetic waves we have the two forces, the magnetic and the inductive, which go hand in hand, and are always at right angles to each other.

It is these electro-magnetic waves that are used in wireless telegraphy, and the same waves, when much smaller in wave-length, produce all the phenomena of light.

Consider a single electron swinging up and down in a vertical path one centimetre long. Let its motion be a simple harmonic motion, like that of a piston-rod; then its velocity will be greatest in the middle of its run, and least at the ends. The

magnetic field due to its motion will therefore be greatest when the electron is passing the centre of its path, and least when its motion is being reversed. On the other hand, the acceleration (and retardation) will be greatest at the ends of the path, and the inductive force due to the electron will be greatest when its motion is being reversed. The electron therefore, sends out two systems of waves into the surrounding space, which are both propagated with the velocity of light, but retarded with respect to each other in such a manner that the maximum of one coincides with the minimum of the other.

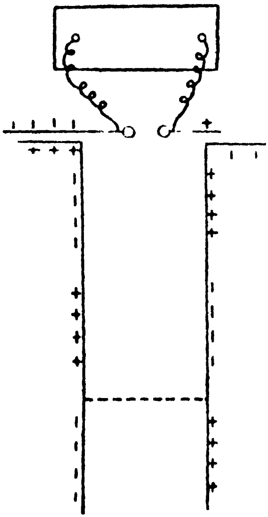

FIG. 28.

A single electron would, of course, not give rise to an appreciable electromagnetic effect; but very perceptible waves may be generated by means of an induction coil discharged through a conductor of some capacity.

Let an induction coil be discharged through a spark-gap, consisting of two metallic knobs, Fig. 28, connected with metallic plates to increase the capacity. The discharge is, of course, oscillatory,

since the primary current in the coil is made and broken in rapid succession. An oscillatory discharge means the surging to and fro of electrons. The number of oscillations per second has been determined by observing the sparks in a revolving mirror. Trowbridge and Duane found a rate of oscillation amounting to five million per second for a small capacity. With a larger capacity the oscillations would be slower.[1]

The oscillations are perceived most easily by mounting two plates facing those attached to the knobs, and stretching out two parallel wires with free ends, as shown. This arrangement is due to Lecher, and is an improvement on the apparatus by which Hertz was first enabled to demonstrate the existence of electric waves.

The surgings of the electrons in the gap produce inductive pulses in the secondary plates, which urge the electrons in them up and down in unison, but always in the opposite direction from the acceleration of the electrons in the gap. These pules are transmitted along the wire, and under their influence the electrons in them are urged to and fro along it, just as particles of water describe circles when a wave passes.

When the pulse or surge of electrons arrives at

[1] The period of oscillation is given by the equation $T = 2\pi\sqrt{LC}$, where L is the self-induction and C the capacity of the circuit.

the end of the wire, it accumulates there and rebounds, just as a water-wave does against a sea-wall. The analogy with the water-wave goes even further. For when a water-wave makes straight for a sea-wall, and is thrown back, it combines with the advancing wave to form stationary waves, and the water moves up and down in the same place, like a violin string. Similarly, the direct and reflected pulses of an electron current combine to form stationary waves in a wire, marked off from each other by "nodes" at which there is no accumulation of electrons, but a very rapid motion to and fro. These nodes, and the "ventral segments" between them, are a well-known phenomenon in the vibration of strings and rods. The distance between two successive nodes is half the wave-length of the electric pulse. When the wires are bridged by a spark-gap, the nodes are marked by the absence of sparks, and the centres of the ventral segments by a maximum of sparking. But a more sensitive detector of waves is a highly exhausted glass tube, which shines out when laid across from one ventral segment to the other, but remains dark at the nodes. When another bridge, consisting of a plain wire, is added, the tube generally ceases to respond, since all oscillations are disturbed. But if the wire is laid across between two nodes, the tube flashes out at a corresponding ventral segment, and is not extinguished even when all the other nodes are

bridged. In this manner the wave-system along the wire may be mapped out, and the wave-length determined experimentally. In one experiment, where the frequency was five million per second, the wave-length was found to be 57 metres. Hence the velocity of propagation was $5 \times 10^6 \times 5700$ cm. per sec., or approximately 3×10^{10} cm. per sec. This is the velocity of light, and thus we have the experimental proof that *electric pulses are propagated along a wire with the velocity of light.*

By reflecting waves in air from a metallic plate, Hertz proved in the same manner that electro-magnetic waves are propagated through air with the same velocity. He thus furnished a brilliant practical confirmation of Maxwell's guess, that light itself is an electro-magnetic phenomenon, and consists of electro-magnetic waves of very short wave-length.

The frequency of the discharge of a condenser is very great, the oscillations being counted by millions per second. Yet it is not great enough to give waves as short as those of light. By diminishing the capacity and inductance of the wave-producing system, Lebedew succeeded in reducing the wave-length to half a centimetre. But since the wave-length of yellow light is so small that 20,000 of its waves go to the centimetre, it is clear that our oscillating systems must be made

more rapid before we can produce light directly by motion of electric charges.

When, however, we recollect that the oscillation of electrons about positive atoms takes place with a frequency of about 10^{15} vibrations per second, the phenomena of light receive a simple explanation. For every electron describing a straight or elliptical path sends out waves of both magnetic and inductive force, and every electron revolving in a circle gives rise to a steady magnetic field, and a revolving field of inductive force.

We have already considered the oscillation of an electron to and fro, and seen that it necessarily sends out waves of magnetic and inductive force which, when of the proper size, must become perceptible to our eyes as light. If too long, they constitute infra-red or heat waves; if too short, they constitute ultra-violet rays, which are powerfully actinic. When, instead of oscillating in a straight line, the electron describes an elliptical orbit, it has both a change of velocity and of acceleration towards its centre of force in the positive atom: but when it describes a circle, its velocity is constant. It experiences a constant acceleration towards the centre of the circle, and this acceleration is effective in producing a pulse of inductive force, though powerless to change the velocity with which the electron revolves. The direction of the acceleration is constantly changing—revolving, in fact—and hence the

inductive force revolves also. The wave sent out into space is a twirl something like what one may produce by laying a string over a table and quickly twisting one end of it. If the wave is visible as light, it is described in optics as "circularly polarised," in a direction depending upon the direction of revolution of the electron. When the electron simply oscillates to and fro, or appears to do so from the point of vision (as a revolving electron appears to do when viewed from one side) the light is said to be "plane-polarised." But the plane of polarisation is not that in which the electron oscillates, but is at right angles to it. For when an electro-magnetic wave is intercepted by glass at a certain angle called the polarising angle, the wave is reflected only when the electric oscillation takes place in a plane normal to the plane of incidence. This experiment disposes of the old controversy with regard to the true motion with respect to the plane of polarisation.

When another revolving electron is met with by a circularly polarised wave—a "twirl," as described above—it retards or accelerates the revolution of the electron. If both revolve in the same direction the revolution of the second electron is retarded by the inductive pulse, which, as we have seen, is always in the direction opposite to the motion of the charge from which the inductive force proceeds.

For the same reason the motion of an electron revolving in a direction contrary to the direction of the radiating electron is accelerated. If the electrons thus impinged upon do not revolve in planes normal to the direction of propagation of the pulse, their acceleration or retardation will be reduced in proportion with the projection of their orbit upon the normal plane. But we see in any case that, whether they are accelerated or retarded, the net effect of the pulse is to counteract the magnetic field which emits the pulse. This also happens when one circuit induces a current in another circuit. But note the important difference. In a wire the inductive impulse fritters itself away in overcoming the resistance of the wire, and converting itself into heat. In freely revolving electrons there is no such waste of energy. A magnetic field suddenly established induces a permanent change of velocity in the orbital motion of the electrons, which lasts until the magnetic field is annulled. That permanent change of velocity always acts in opposition to the field whose creation produced it. Now, when a body is magnetised in a direction opposed to the direction of the field, we call it "diamagnetic." We are, therefore, driven to the conclusion that all bodies containing electrons in orbital motion round atoms are diamagnetic. The Zeeman effect shows that all bodies contain such electrons, therefore *all known substances are funda-*

mentally diamagnetic. But since the change of velocity actually produced does not exceed 1 part in 100,000, it is almost inappreciable as a rule; and when the orbital circuits influence each other sufficiently to swing round into line, the paramagnetic effect is sufficient to completely mask the fundamental diamagnetism of the substance.

The above considerations make it clear why some substances absorb light while others do not. Those substances which contain free electrons not permanently bound to separate atoms allow their electrons to follow freely the magnetic and inductive forces at play within the light-wave, and the motion thus produced is absorbed and frittered away into heat. These substances are the good conductors, more especially the metals. Solutions, whose ions have a mobility far below that of electrons in metals, are much more transparent than the latter, and the insulators, especially those of a low dielectric constant, absorb light least. It is also readily understood that when electrons in an illuminated body happen to be revolving with the same period as the incident light, the change of velocity is much greater than if they are not. Their orbital equilibrium is more easily upset, and the electrons fly away from their atoms and roam at large. This is what is called "optical resonance." It accounts for the fact that some wave-lengths of

light are more easily absorbed than others. It accounts, in fact, for the phenomena of *colour*. It also makes clear to us why a body absorbs most easily light of the same colour and wave-length as that which it emits itself—a fundamental and important law of radiation.

CHAPTER XI

MEASUREMENTS CONCERNING ELECTRONS

In this chapter I intend to specify the experiments which have led to the general acceptance of the electron theory, and brought the scientific world face to face with the electron itself. Hitherto I have taken the electron for granted, and the reader may have been inclined to wish for some evidence of the existence of a body over 1000 times lighter than the atom of hydrogen, which latter has been until recently regarded as the smallest possible material particle. That evidence shall now be furnished.

When a vacuum tube is exhausted to one-millionth of an atmosphere, the luminous phenomena previously observed give way to the phenomenon of cathode rays, which proceed in straight lines from the cathode or negative electrode, and produce a green fluorescence on the walls of the tube.

These cathode rays are electrons, projected by the cathode with an enormous velocity.

That this is so is proved by the following facts:—

1. The "rays" convey a negative charge.

2. They consist of minute particles of matter.

3. These particles have a constant charge, amounting to $3{\cdot}4 \times 10^{-10}$ electrostatic unit.

4. The particles have a mass about a thousand times smaller than the hydrogen atom.

5. They move with a velocity little less than that of light.

These facts were gradually recognised as the result of a large number of difficult and often highly ingenious experiments undertaken with a view to elucidate the nature of cathode rays. When the experiments were first undertaken nobody expected to find the cathode particles to be identical with the electrons postulated by Lorentz in order to explain the Zeeman effect. Many experimenters actually thought that the cathode rays were electro-magnetic waves, and claimed to have proved that they were. It was only when new and crucial experiments were made, and successfully repeated everywhere, that the truth was made manifest to a wondering world. That was in the year 1897, and since that year the electron has become the corner-stone of electrical science.

That the cathode rays convey an electric charge was already proved by Jean Perrin in 1895. His apparatus is illustrated in the diagram (Fig. 29), which shows a vacuum tube provided with two electrodes.

The cathode C is a disc of aluminium, and the

anode A B D E is a box of aluminium with an opening towards the cathode. Inside this box is a hollow cylinder, F, connected with an electroscope or an electrometer. When the tube is sufficiently exhausted and a current sent through it, cathode rays are projected from C into the box and the inner cylinder, which at once acquires a negative charge. That this charge is really due to the rays is proved

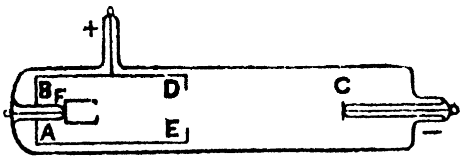

FIG. 29.

by deflecting the cathode beam with a magnet, whereupon F remains uncharged.

If, then, the rays consist of charged particles, the next question is as to the size and charge of each individual particle, and the velocity with which it is moving.

There are several different ways of determining these. The most obvious way is to expose the particles to a lateral pull. When water is projected from a horizontal orifice the jet describes a parabola under the influence of the earth's attraction. The distance to which the jet carries depends upon the force with which it is projected—in other words, upon its velocity. The greater that velocity, the less

will the jet fall towards the ground in traversing a given portion of its path. Now the cathode beam is a jet of electrified particles, travelling at such a prodigious rate that their weight exerts no perceptible effect upon their path. But stronger deflecting forces are readily available. Since it is the electric field between the cathode and anode that generates their velocity, another field acting at right angles to their

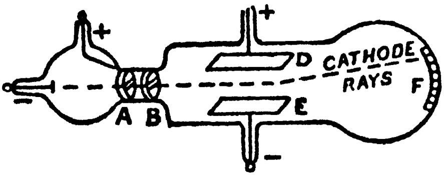

FIG. 30.

path will produce a strong deflection. The apparatus used by J. J. Thomson to perform this experiment is shown in Fig. 30. C is the cathode, A and B are thick metallic diaphragms serving as the anode, and provided with horizontal slits. The deflecting electric field is established between the plates D and E, which are large enough to give a fairly uniform field. The cathode beam is made into a narrow horizontal strip in passing through A and B, and this strip is bent into a parabola while traversing the field between D and E, and after leaving this it continues in a straight line till it impinges on a scale, F, which measures its deflection.

Now the effect produced by the deflecting field

depends upon three factors. One of these is the speed of the particles, which we have already referred to. Another is their electric charge, which controls the force exerted by the field upon them. Evidently the greater their charge the more will they be deflected. The third factor is the mass of the particles. The greater their mass—*i.e.* their inertia—the more force will be required to deflect them from their path. If e is the charge of a particle, and m its mass, its deflection is proportional to $\frac{e}{m}$. This all-important ratio becomes known as soon as the velocity of the particles is determined. Its interest is enhanced by the fact that in electrolysis the ratio of the electricity transported to the mass transported is fixed for each element, being 95,000 coulombs per gramme in the case of hydrogen. The discovery of a similarly constant ratio in gaseous discharges was therefore eagerly sought after.

Since there are two unknown quantities, $\frac{e}{m}$ and v (the velocity), we require two independent equations in order to determine them. The electric deflection furnishes one equation. The other may be derived either from the magnetic deflection, from the difference of potential, or from the heat developed.

A method devised by Wiechert, and employed by d'Arsonval, is particularly effective in determining directly the velocity v. It is based upon the deflection of cathode rays by a magnetic field. We have

seen above (p. 147) that an electron in motion is attracted by another moving parallel to it. If the electrons were free to move in any direction, and not forced to move along a wire, they would approach each other. A wire bearing a current exerts a similar "magnetic" force upon moving electrons by virtue of the electrons moving along it. The force is directed towards the wire; but since the "lines of magnetic force" (*i.e.* the lines along which a magnetic pole would move) are circles round the wire, the attraction exerted upon a moving electron is at right angles to the lines of magnetic force. If, therefore, a vacuum tube is placed between two magnet poles so that the magnetic lines of force cross the path of the cathode rays horizontally, the rays are deflected up or down according to the polarity of the lines of force. When the magnetic field is due to the poles of an electro-magnet fed by an alternating current, the cathode beam is deflected up and down with the frequency of the alternate current itself, and the fluorescent spot which it produces on the glass wall, or better, on a special fluorescent screen, moves up and down as the direction of the current changes. Now it is found that whatever may be the frequency of an alternating current, the luminous spot follows the alternations instantly. No undulation can be observed along the cathode beam as it is observed in the case of a rope swung up and down at one end. This shows already, without further confirmation,

that an almost incredibly short time must elapse between the cathode particle leaving the cathode and arriving at the wall. But the time taken can be actually measured by means of two successive electro-magnets placed some distance apart and traversed by the same high-frequency current. M. d'Arsonval succeeded in bringing a current of the enormous frequency of 10,000,000 oscillations per second to bear upon the rays. He then placed a slit just beyond the first electro-magnet, so as to shut off all the cathode rays except those which produced the luminous spot highest on the screen. These are the rays that passed the first magnet, just at the maximum of magnetisation in one direction. On passing the second electro-magnet, the cathode rays are again deflected in the same direction; but on placing the electro-magnets further apart and taking care that they are always in the same magnetic state at a given instant, a position is found in which the second electro-magnet produces no further deflection. This happens when the time taken by the cathode rays to traverse the distance between the two electro-magnets is one-quarter of the period of the alternating current; for then the magnetising current, being midway between two opposite maxima, is zero. Now the period being a 10,000,000th of a second, this quarter-period is a 40,000,000th of a second. M. d'Arsonval found the proper distance between the electro-magnets to be 75 centimetres. Hence the

speed of propagation of the cathode rays or projected electrons was 75×40 millions $= 3000$ million cm. per sec., *or one-tenth of the velocity of light.*

This startling result leads to some surprising conclusions. The velocity is a million times greater than that of the fastest express train, and a milligramme of matter moving with that speed has ten times the destructive energy of a railway train at top speed.

This velocity being known, the ratio $\frac{e}{m}$ can be determined from the electrostatic deflection. But it is simpler to determine it from the magnetic deflection itself. The magnetic force upon the electron is always at right angles to its path. That path must therefore be an arc of a circle as long as it lies in the magnetic field and the field has a constant strength. The curvature of the path may be calculated from ordinary mechanical principles. The centripetal force equals the product H e v, where H is the magnetic field and e the charge. The centrifugal force is $\frac{m v^2}{r}$, where m is the mass of the electron, v its velocity, and r the radius of curvature. Hence

$$H e v = \frac{m v^2}{r}$$

or

$$H \frac{e}{m} = \frac{v}{r}$$

or

$$\frac{e}{m} = \frac{v}{H r}$$

The value obtained by Wiechert in 1899 was 465×10^{15}, meaning that a gramme of cathode rays represents a charge of 465,000 billion electrostatic units or "companies" of electrons.

Instead of measuring the velocity, it may be eliminated between two equations by calculating it from the observed difference of potential, which must impart to the particles a velocity simply depending upon $\frac{e}{m}$. In this manner, Kaufmann found, in 1898, the value 558×10^{15}, and Simon in 1899: $559 \cdot 5 \times 10^{15}$. Other methods, capable of greater or less accuracy, have been devised and employed by J. J. Thomson, Lenard, Becquerel, and others; but they all confirm the order of magnitude found above.

A very important and significant observation made by all was that the ratio $\frac{e}{m}$ depends neither upon the gas contained in the vacuum tube nor upon the metal of the electrodes. This result is surprising if the cathode rays are atoms of ordinary matter. It would mean not only that ordinary matter is capable of travelling with a speed approaching that of light; but that every atom has an electric charge proportional to its weight. For such a state of things there is no precedent. In electrolysis every atom conveys a charge proportional to its valency and quite independent of its weight. The atoms of magnesium, zinc, and cadmium, whose weights are in the pro-

portion of 24 : 65 : 112, each convey exactly the same quantity of electricity through the electrolytic cell. It would be strange if the amounts of electricity they conveyed through the vacuum tube were as 24 : 65 : 112.

But there is an even more remarkable difference between cathode rays and electrolysis. In electrolysis the ratio $\frac{e}{m}$, or the charge conveyed by unit mass of the electrolyte (or required for decomposing it), varies from one metal to another, m changing from one atom to another, while e remains constant except for changes of valency. For hydrogen, the lightest of the known elements, the ratio $\frac{e}{m}$ is $0{\cdot}286 \times 10^{15}$, or about 2000 times smaller than the same ratio for cathode rays. This means that the mass conveying the atomic charge is either 2000 times larger than the mass of the cathode particle, or that the charge of the hydrogen atom is 2000 times smaller than that of the cathode particle.

The former alternative seemed barred by the impossibility of assuming the existence of anything smaller than the atom of hydrogen. The whole tradition of the atomic theory rebelled against such an idea. Nevertheless the next great step in discovery was the momentous one of determining the actual charge and the actual mass of the cathode particles, and thus to establish not only the existence of material particles much smaller than atoms, but

the existence of a primordial form of electric matter hitherto unknown.

The Cavendish Laboratory at Cambridge will be for ever memorable as the place where this momentous measurement was first carried out. The measurement was in the first instance not made with cathode rays, but with the slowly moving particles which are the chief agents in gaseous conduction.

When a gas is put into a conducting state, say, by exposure to Röntgen rays, it remains for a little time in that state, even after the rays have ceased. If, however, the gas is bubbled through water, or filtered through a plug of cotton wool, its conductivity disappears. Again, when the gas is passed between two plates, one of which has a high negative charge, while the other is insulated, the negative particles will all be driven against the insulated plate, and their total charge can be measured by an electrometer connected with the plate. This charge is evidently equal to $n\,e$, where n is the number of particles, and e their charge. The total charge $n\,e$ being measured, it remains to determine n in order to find e, the charge on each particle. This is J. J. Thomson's famous "counting experiment," which is best described in his own words:[1]—

"The method by which I determined n was founded on the discovery by C. T. R. Wilson, that

[1] J. J. Thomson, "Electricity and Matter," 1904, p. 75.

the charged particles act as nuclei round which small drops of water condense when the particles are surrounded by damp air cooled below the saturation point.

"In dust-free air, as Aitken showed, it is very difficult to get a fog when damp air is cooled, since there are no nuclei for the drops to condense around. If there are charged particles in the dust-free air, however, a fog will be deposited round these by a supersaturation far less than that required to produce any appreciable effect when no charged particles are present. Thus, in sufficiently supersaturated damp air, a cloud is deposited on these charged particles, and they are thus rendered visible. This is the first step towards counting them. The drops are, however, far too small and too numerous to be counted directly. We can, however, get their number indirectly as follows: Suppose we have a number of these particles in dust-free air in a closed vessel, the air being saturated with water vapour. Suppose, now, that we produce a sudden expansion of the air in the vessel. This will cool the air; it will be supersaturated with vapour, and drops will be deposited around the charged particles. Now, if we know the amount of expansion produced, we can calculate the cooling of the gas, and therefore the amount of water deposited. Thus we know the volume of water in the form of drops, so that if we know the volume of one drop we can deduce the number of drops.

To find the size of a drop we make use of an investigation by Sir George Stokes on the rate at which small spheres fall through the air. In consequence of the viscosity of the air small bodies fall exceedingly slowly, and the smaller they are the slower they fall. Stokes showed that if a is the radius of a drop of water, the velocity v with which it falls through the air is given by the equation

$$v = \frac{2}{9}\,\frac{g a^2}{\mu}$$

where g is the acceleration due to gravity = 981, and μ the coefficient of viscosity of air = 0·00018. Thus

$$v = 1{\cdot}21 \times 10^6 a^2;$$

hence, if we can determine v we can determine the radius, and hence the volume of the drop. But v is evidently the velocity with which the cloud round the charged particle settles down, and can easily be measured by observing the movement of the top of the cloud. In this way I found the volume of the drops, and thence n the number of particles. As ne had been determined by electrical measurements, the value of e could be deduced when n was known. In this way I found that its value is

$$3{\cdot}4 \times 10^{-10} \text{ electrostatic c.g.s. units.}$$

Experiments were made with air, hydrogen, and carbonic acid, and it was found that the ions had the

same charge in all these gases—a strong argument in favour of the atomic character of electricity."

The ratio $\frac{e}{m}$ is the same for cathode rays, for negative carriers of gaseous discharges, and for the negatively electrified particles emitted by metals when exposed to ultra-violet light, or raised to the temperature of incandescence. In each case the charge of each particle is the same, while its mass is less than a thousandth of the mass of the hydrogen atom. J. J. Thomson proposed the name "corpuscle" for these natural units of negative electricity. "These corpuscles are the same, however the electrification may have arisen, or wherever they may have been found. Negative electricity in a gas at a low pressure has thus a structure analogous to a gas, the corpuscles taking the place of the molecules. The 'negative electric fluid,' to use the old notation, resembles a gaseous fluid with a corpuscular, instead of a molecular, structure."

Instead of the word "corpuscle," the new word "electron," proposed by Dr. G. Johnstone Stoney, has now been almost universally adopted as being more specialised and unmistakable. Prof. Thomson sums up his conclusions in the following passage, in which I have substituted "electrons" for "corpuscles":[1]—

"These results lead us to a view of electrifica-

[1] J. J. Thomson, "Electricity and Matter," 1904, p. 88.

tion which has a striking resemblance to that of Franklin's 'One-Fluid Theory of Electricity.' Instead of taking, as Franklin did, the electric fluid to be positive electricity, we take it to be negative. The 'electric fluid' of Franklin corresponds to an assemblage of electrons, negative electrification being a collection of these electrons. The transference of electrification from one place to another is effected by the motions of electrons from the place where there is a gain of positive electrification to the place where there is a gain of negative. A positively electrified body is one that has lost some of its electrons. We have seen that the mass and charge of the electrons have been determined directly by experiments. We in fact know more about the 'electric fluid' than we know about such fluids as air or water."

Since these remarkable experiments were performed, they have been repeated again and again with constantly increasing precision. The electrons have been rediscovered in several other fields of research, notably the phenomena presented by radium, one of whose radiations is constituted by cathode rays or projected electrons. The ratio $\frac{e}{m}$ and the values of e and m are now known with considerable accuracy, though the ratio is still much better determined than its two constituents. Side by side with the advances on the experimental side have been the theoretical advances. The

electron theory has been developed in its mathematical aspects, and has given occasion for many notable results and speculations. But the measurements made between 1896 and 1898 and outlined above form the foundation on which the imposing structure of the electron theory has since been raised.

CHAPTER XII

ELECTRICITY AND LIGHT

THE discovery that light consists of waves of electric and magnetic force (p. 200) has vastly extended the spheres both of electrical and of optical science. But that discovery was made before the days of the electron theory, and was embodied mathematically in a set of differential equations, having but a slender connection with the structure of actual matter. The electro-magnetic theory of light replaced the older theory, which regarded the ether as behaving like an elastic solid wherever very rapid vibrations were concerned. But the experimental basis of the electro-magnetic theory was meagre, and it left a vast array of facts entirely unexplained, notably those of the absorption and dispersion of light. Indeed, its chief exponents were always careful to point out that they knew nothing concerning the intimate structure of those materials whose specific inductive capacities or magnetic permeabilities figured in their formulæ. In his "Theory of Optics," Prof. Schuster refers to this tendency as follows:—

"There is at present no theory of optics in the

sense that the elastic solid theory was accepted fifty years ago. We have abandoned that theory, and learnt that the undulations of light are electromagnetic waves differing only in linear dimensions from the disturbances which are generated by oscillating electric currents or moving magnets. But so long as the character of the displacements which constitute the waves remains undefined, we cannot pretend to have established a theory of light. This limitation of our knowledge, which in one sense is a retrogression from the philosophic standpoint of the founders of the undulatory theory, is not always sufficiently recognised, and sometimes deliberately ignored. Those who believe in the possibility of a mechanical conception of the universe, and are not willing to abandon the methods which from the time of Galileo and Newton have uniformly and exclusively led to success, must look with the gravest concern on a growing school of scientific thought which rests content with equations correctly representing numerical relationships between different phenomena, even though no precise meaning can be attached to the symbols used. The fact that this evasive school of philosophy has received some countenance from the writings of Heinrich Hertz, renders it all the more necessary that it should be treated seriously and resisted strenuously."

The electron theory, by dealing with the elementary carriers of electricity, has brought a powerful

new weapon to bear upon optical problems, and has already accomplished a great deal in the way of their elucidation. But it will be some time before the facts of optics are completely marshalled in order, and linked with those of chemistry, electricity, and magnetism. Their variety is almost infinite, and their full explanation involves revolutionary changes in the theory, not alone of optics, but of chemistry as well. I shall, therefore, have to content myself with a brief outline of the main facts.

(*a*) *Refraction.*—All electro-magnetic waves are transmitted with the velocity of light (3×10^{10} cm. per sec.) in media free from electric charges. This is one way of stating the electron theory of refraction. It means that when the progress of a wave is retarded, that retardation is due to the presence of electrons or positive atoms. It is this presence of electrons which accounts for the specific inductive capacity or dielectric constant of a medium (see p. 62), and Maxwell's theory indicates a simple relation between the velocity of propagation v of an electro-magnetic wave through a medium, and its dielectric constant K. It is as follows:—

$$v^2 = \frac{1}{K};$$

that is to say, the square of the velocity of the wave varies inversely as the dielectric constant. Let us

see what information our theory can give us in this matter.

The force between two charged bodies possessing charges E and E^1, and placed d cm. apart, is

$$\frac{E E^1}{K d^2}.$$

That is to say, the force decreases as the dielectric constant increases. Now, according to our theory, a "dielectric" is a body consisting of molecules or atoms, to which electrons are closely attached in such a manner that very few of them roam at large among the atoms. When a dielectric is introduced between two condenser plates charged positively and negatively respectively, the electrons are pulled towards the positive plate, and the positive atoms towards the negative plate. Each electron is, therefore, separated from its atom; but not so far as to be pulled away by the next atom. The electrons on the surface facing the positive plate will constitute a negative surface charge, and the positive atoms facing the negative plate constitute a positive surface charge; and these surface charges, by freeing the interior of the dielectric from some of the electric force, reduce the internal field, and thus also reduce the difference of potential between the condenser plates, thereby increasing the capacity of the condenser. So much for the dielectric constant.

Now, as regards the propagation of waves. Let an

oscillatory current surge up and down one of the plates; in other words, let the free electrons in the plate be made to oscillate up and down in rapid succession. This, as explained on p. 179, leads to a downward and upward thrust of all electrons in the neighbouring space. In the upper half of its path the oscillating electron is exposed to a downward force, and therefore sends out an upward impulse into surrounding space. Any electron which follows this impulse will therefore oscillate in a reverse direction, and will neutralise to some extent the effect of the original oscillation in the space beyond, just as in transmitting oscillations along a stretched string the weight of an element of length shields the further elements for a short time. The more electrons capable of oscillation there are in the dielectric, and the feebler the forces which tend to keep them in position, the slower will be the rate at which an electric wave is propagated. These are the same conditions as those which account for a high dielectric constant. It is, therefore, clear that a high dielectric constant means a slow rate of wave-propagation, and *vice versâ*. The exact numerical relation between the two quantities is not apparent from these simple considerations; but a glance at the ordinary laws of wave-propagation will explain Maxwell's law in an elementary manner. Whenever a wave is propagated through a medium, we find that the velocity of propagation is proportional to

the square root of the force which tends to bring back the body into its place when pulled out of it. Now, in the case of an electron subject to periodic impulses in opposite directions, the velocity with which it follows the impulses of the original oscillation and those of other intervening electrons depends upon the strength of the impulses so transmitted Now, the force across a dielectric varies, as we have seen above, inversely as the dielectric constant K Hence the velocity of propagation, which varies as the square root of the force, will vary as $1/\sqrt{K}$ Hence

$$v^2 = \frac{1}{K}.$$

This relation holds good as long as the oscillations in the condenser plate are slow, and far below the natural period of oscillation of electrons about their positive atoms.

When an electro-magnetic wave reaches a dielectric, its velocity is reduced. When it hits its surface at right angles, it is propagated in the same direction, only more slowly than before, and the wave front is always parallel to the surface. When, however, the wave arrives at an angle to the surface, the portion which arrives first begins to be retarded sooner than the rest, and the wave front is bent round or "refracted." The laws of refraction are adequately dealt with in the older textbooks of optics.

(*b*) *Dispersion and Colour.*—Prismatic effects and dispersion generally are due to some waves being propagated more slowly than others. They are therefore refracted to different degrees, and separated into the well-known optical spectrum. This phenomenon is called dispersion. It is memorable that the theory of dispersion was the breeding-ground of the electron theory. A theory involving the displacements and vibrations of elementary charges had been applied to dispersion by Prof. Lorentz, of Amsterdam, for several years before it was confirmed by the discovery of the Zeeman effect. In fact, the phenomena of dispersion had always been the great stumbling-block in the way of the Maxwell-Hertz theory, which told us nothing about them. The electron theory of dispersion has been worked out mainly by Schuster in Manchester and Drude in Giessen. It is embodied by the latter in an equation[1] which might as well be quoted here, as it states the matter very concisely. It is

$$n^2 = 1 + N\theta + \frac{N\theta L^2}{\lambda^2 - L^2}.$$

In this equation n is the refractive index, N the number of electrons per cubic centimetre, λ the wave-length of the incident light, L the wave-length of the natural wave emitted by the electrons in their ordinary oscillation, and θ is inversely proportional to the force tending to keep the electrons in their

[1] P. Drude, *Annalen der Physik*, No. 9, 1904, p. 681.

central positions. For short, we might call θ the "laxity."

Many interesting results may be read in this equation. In the first place, if $N = 0$, $n^2 = 1$, and $n = 1$. That is to say, the velocity in the dielectric is the same as in pure ether. It is only the electrons which retard the wave. Further, the greater the "laxity" θ, the greater is the refractive index, and the slower the wave in the dielectric. This has already been mentioned under refraction.

The first and second terms on the right-hand side are independent of the wave-length λ, and if only those terms had to be considered, there would be no dispersion. The third term, however, involves λ, and we see at once that its amount depends both upon the wave-length of the incident light and the natural waves emitted by the vibrating electrons. If λ is very large in comparison with L, we may neglect L^2 in comparison with λ^2, and put $\lambda^2 - L^2 = \lambda^2$, and the third term becomes approximately

$$= \frac{N\theta L^2}{\lambda^2}.$$

As λ becomes gradually smaller, this term becomes gradually larger, and hence also n becomes gradually larger. This means that *the shorter the waves are the more they are refracted.* Any one observing a spectrum formed by a prism will see that the blue rays, which have a shorter wave-length, are more deviated than the red rays, which have a greater

wave-length. This is what is called *normal dispersion.*

When λ is extremely large—*i.e.* the incident oscillation extremely slow—the third term becomes zero, and the equation reduces to

$$n^2 = 1 + N\theta.$$

This is independent of the wave-length, so that *very long waves are not dispersed.* They are all propagated with the same velocity, which simply depends upon the density and "laxity" of the electrons in the medium. This dependence may be arrived at by remembering that the "refractive index" n of a medium is the ratio of the velocity of propagation of light in the ether to the velocity in the medium—

$$n = \frac{V_1}{V}$$

where V_1 is 3×10^{10} cm. per sec. Thus we have

$$n^2 = \frac{V_1^2}{V^2} = 1 + N\theta.$$

Or $$V^2 = \frac{V_1^2}{1 + N\theta}.$$

This last equation teaches us several valuable things. For long waves, the velocity of propagation in a dielectric depends upon the velocity in the ether, and upon a term involving the density and laxity of the electrons in the medium. The more electrons there are, and the more easily they are displaced from

their positions, the more slowly will the long waves travel through them. But we have also seen that

$$V^2 = \frac{1}{K}.$$

Therefore we have

$$\frac{V_1^2}{1 + N\theta} = \frac{1}{K},$$

or

$$K = \frac{1 + N\theta}{V_1}.$$

This is an important formula defining the specific inductive capacity (or "dielectric constant") K in terms of the electron theory. It may be calculated if we know the density and laxity of the electrons in the substance. And, conversely, we may calculate the product of the density and laxity if we know thediel ectric constant.

To return to Drude's equation—

$$n^2 = 1 + N\theta + \frac{N\theta L^2}{\lambda^2 - L^2}.$$

When λ becomes smaller and smaller the third term becomes larger and larger, and the refraction becomes more and more pronounced. When $\lambda = L$—*i.e.* when the incident light has the natural periods of the electrons—an extraordinary situation is created. The denominator becomes zero, and therefore the whole fraction becomes infinite. Hence n^2 also becomes infinite, and the velocity of propagation becomes zero. *The wave is stopped.* If λ decreases

still further, the denominator increases again, but becomes a negative quantity. This means that the refractive index is diminished instead of being increased. When the difference $\lambda^2 - L^2$ is still excessively small, the third term is an excessively large negative quantity, and may well be much larger than the second term. In this case we shall have the still more extraordinary situation that n^2 is smaller than unity: in other words, that a vibration very slightly shorter than the natural vibration of the electrons *is propagated with a velocity greater than that of light.*

When λ diminishes still further the denominator increases and the third term as a whole becomes smaller. The limit is reached when $\lambda = 0$, and then we have

$$n = 1 + N\theta + N\theta\frac{L^2}{L^2} = 1 + 2N\theta,$$

so that here again we have a limiting value for infinitely short waves, which is somewhat higher than the value for infinitely long waves, and again independent of the wave-length. Infinitely short waves are therefore not dispersed either.

In general, we have the important conclusion that electrons or other charged bodies only influence the velocity of propagation of the incident wave *when the period of oscillation of that wave happens to be not very different from their own.*

The extraordinary occurrences which take place when the two periods of oscillation nearly coincide are known as *anomalous dispersion.*

(*c*) *Absorption and Reflection.*—When the wave-length of the incident light-wave happens to be the same as the natural wave-length emitted by the electron, the wave is stopped. As we have seen in the elementary case investigated above, the electrons are always in the phase opposite to that of the original oscillation. They, therefore, compensate the incident wave, and prevent it from exerting any effect inside the body. But in doing so they must, of course, absorb more energy than they do in their natural state. The usual consequence is that they are shaken and swung out of their normal orbit in the neighbourhood of their positive atoms, and shot off into the interior of the substance, there to roam at large and collide with other atoms in rapid succession. Each of these collisions means a stoppage of an electron, and hence an electro-magnetic wave impulse. These irregular impulses constitute radiant heat, which travels away into space and is lost. The whole process is termed absorption. It means that the incident light is not transmitted, but converted into heat in the manner stated.

But it may happen that the electrons are not thus shaken off, but continue to vibrate in accordance with the period of the incident vibration, or rather, half a period behind it. Then they will

practically constitute a set of independent sources of light, and will radiate the light out into the space on the side of the incident light. In fact, we shall have *reflection*. When the surface is quite smooth, and dotted evenly with electrons of the same period, the reflection will be "regular" or geometrical. The angle of reflection will be equal to the angle of incidence. The explanation is the same as that given in the ordinary textbooks, and is based upon Huyghen's principle.

In practice, it is found that most bodies can be "polished," and that all bodies reflect some light. This means that all known bodies contain some electrons, however small in number, which vibrate in the period of the incident light.

(*d*) *Polarisation.*—Light may consist of various species in accordance with the manner in which the electro-magnetic vibration takes place. When the electron vibrates in the same straight vertical line, the light is said to be plane-polarised in a horizontal plane. When it vibrates in a circular orbit, the light emitted along the axis of the orbit is "circularly polarised," and this circular polarisation may be either right-handed or left-handed, according to the direction of rotation. When the orbit is an ellipse, the light is elliptically polarised. Finally, the electrons, or a large aggregate of them, may send out light in all kinds of polarisation in turn, and then we have ordinary or natural light.

Ordinary light may be converted into plane polarised light by sending it through a body whose electrons are capable of vibrating in one plane only, as in tourmaline. The transmitted light will then be found to be plane-polarised in a plane at right angles to that direction of vibration.

(*e*) *Double Refraction.*—Calcspar is a carbonate of calcium of the formula $CaCO_3$. Each molecule contains five electrons capable of vibrating pretty freely. But only two of these are capable of vibrating in the direction of the crystallographic axis. The other three, if they vibrate along that axis at all, do so with a very great rapidity, implying a very small "laxity," θ. The consequence of this is that when a beam of light is sent through calcspar at right angles to the axis, only two electrons per molecule take part in the vibration. The term $N\theta$ in Drude's equation is small. Hence the refractive index is small, and the velocity of propagation great. When, on the other hand, a beam of light is sent along the axis, all the five electrons are free to take part. $N\theta$ is larger, n is larger, and the velocity is smaller. Hence light is more slowly transmitted along the axis than across it. This gives rise to the phenomena of double refraction.

(*f*) *Optical Rotation.*—When a plane-polarised beam of light is transmitted through turpentine, a sugar solution, a plate of quartz, or other substances, its plane of polarisation is found to have been turned

on emergence. This would be difficult to explain but for the fact that a harmonic vibration in a straight line may always be considered as made up of two circular vibrations in opposite directions.

One of these circular vibrations is transmitted with greater speed than the other, and when the two circular beams recombine into a plane-polarised beam on emergence, the plane has been turned round in the direction of the circular vibration which has been transmitted more rapidly.

In crystals this rotation may be considered as due to a greater ease of acceleration of electrons in one direction than in another, owing to the configuration of the atoms in the molecule and the piling of the molecules in regular rows. In solutions and liquids, on the other hand, it must be due to unsymmetrical structure of the molecule alone, which is the same from whichever side it is viewed. For the rotation takes place in the same sense whatever may be the direction of transmission. As a matter of fact, Becquerel has shown that the molecules of all substances showing optical rotation (or "rotatory polarisation") in the liquid state, contain unsaturated carbon atoms.

CHAPTER XIII

MAGNETO-OPTIC PHENOMENA

THE connection between magnetism and light was long sought after before the time of Faraday, who was the first to discover a phenomenon linking those two domains of physics. It is now known that magnetism influences the plane of polarisation of light, both when the magnetic field is applied to the source of light and when it is applied to the material which transmits the light. The first effect is known as the Zeeman effect. The last is called magneto-gyration or magneto-optic rotation, and includes the effects discovered by Faraday, Kerr, and Macaluso and Corbino.

(*a*) *The Zeeman Effect.*—In dealing with the phenomena of radiation and of diamagnetism, we have become familiar with the effect of a magnetic field upon the rate of revolution of an electron round a positive atom. We have seen that whatever change it produces, that change tends to oppose the magnetic field which produces it. Diamagnetism is a kind of permanent electro-magnetic induction. We know that induced currents are always opposed to the charge which induces them. It is as if the

electric momentum—the momentum of electric charges—destroyed in one body reappeared in another, just as in a collision there is a transfer of momentum; but the sum of all momenta remains the same, action and reaction being equal and opposite. Ordinary induced currents are of short duration, simply because the electrons set in motion fritter away all their energy in collision with neutral atoms. If the induced currents are of molecular dimensions, and consist in the acceleration or retardation of the rate of revolution of the electron round the positive atom, they are permanent so long as the inducing field remains at the same value. When the field is annihilated, the acceleration it produced is converted into a retardation, and *vice versâ*.

All bodies are fundamentally diamagnetic, and in all of them, therefore, the effects above indicated take place whenever the magnetic field changes. They are brought into evidence by the magneto-optic effects now to be described.

That a magnetic field exerts an action upon the light transmitted through a magnetised medium was already known since Faraday's last researches. But an effect of a magnetic field upon the spectrum of a flame, that is to say, upon a source of light, had been looked for repeatedly without success. The credit of having discovered this effect and furnished its mathematical explanation belongs ex-

clusively to Holland. Dr. P. Zeeman, of Leyden, announced his discovery in 1897, having failed on a previous occasion to find any effect. With the aid of a strong magnet and better spectroscopic apparatus than any of his predecessors had used, Zeeman attacked the problem the second time with success. He placed a Bunsen flame containing common salt between the poles of the electro-magnet and focussed the light on the slit of his spectrometer, arranging the flame so that the D-lines were sharply defined. As soon as the magnet was excited both lines widened out very much. By a careful series of subsidiary experiments he showed that the widening was due directly to the action of the field, and was not a secondary effect such as might be caused by changes of density in the flame.

These results were communicated before publication to Prof. Lorentz, who showed Dr. Zeeman that the widening could be predicted from Lorentz's theory that light is generated by the vibrations of electrically charged particles or electrons; and that the same theory indicated that the edges of the widened lines should be plane-polarised or circularly polarised according as the light falling upon the slit came from the source in a direction perpendicular or parallel to the lines of magnetic force, and that the amount of the widening would give the ratio of the charge to the mass of the

luminous particles. Zeeman was able to verify fully the predictions as to polarisation, and deduced from Lorentz's equations, as a rough value for the ratio $\frac{e}{m}$, the value 10^7 electro-magnetic units per gramme. This is about one-half of the value of the ratio for electrons as determined subsequently.

Further investigation soon showed that the apparent broadening of the lines was in reality due to their being split up into several components. This splitting up was different in accordance with the direction along which the beam of light from the source traversed the magnetic field. When the source was viewed along the lines of magnetic force the D-lines appeared double, and when the line of view was at right angles to the lines of force the D-lines appeared treble. The polarisation of the lines also differed according to the line of view, the doublets consisting of two lines circularly polarised in opposite directions, and the triplets consisting of plane-polarised lines, the plane of the central line being at right angles to that of the side lines. These various effects were completely accounted for by the electron theory tentatively formulated by Prof. Lorentz of Amsterdam. This theory had been regarded as purely speculative until it received this startling confirmation. The discovery of the Zeeman effect, in conjunction with Thomson's counting experiment, made the specula-

tion into a theory of unprecedented generality and fruitfulness.

In view of the importance of the Zeeman effect, I shall endeavour to make its theory as clear as possible, and the student will do well to master it, even at the cost of some effort.

Lorentz's theory supposed that luminous vibrations are due to the rotation of "electric molecules" about attracting masses. Lorentz knew nothing about the charge or mass of these molecules when he formulated his theory, and does not seem to have suspected their identity with the carriers of electricity in electrolysis. He supposed them to rotate in all kinds of directions at random, and in orbits varying from a circle to an ellipse, and even a straight line. Knowing that a charged body is deflected out of its path by a magnet, he was quite prepared to find that the orbits were influenced by a magnetic field, but had no data to enable him to guess whether such an effect could be discovered experimentally. But when the effect was observed, his theory enabled him at once to explain it, and even to give particulars which had not yet been observed, but which further experiments immediately verified.

Consider a beam of light from a sodium flame mounted between the poles of a powerful electromagnet, giving a field of 5000 units, and viewed along the lines of magnetic force, through per-

forations made for that purpose in the pole-pieces. A delicate spectrometer shows the two yellow sodium lines D_1 and D_2, having wave-lengths of 589·6 and $589·0 \times 10^{-7}$ cm. respectively, with a dark interval between them. As soon as the electro-magnet is excited, the lines broaden out to nearly twice their ordinary width, and when a larger magnifying power is used, each line is seen to be split into two, the interval being about $\frac{1}{50}$th of that between the original lines. This means that the period of the original vibration has been changed by about $\frac{1}{100000}$th of its value in each component. This effect is very small, but still discoverable with the best modern apparatus.

The original vibration thus modified consists of the rotation of electrons about positive atoms. These take place in all sorts of planes, but we need only consider the projections of their orbits upon the cross-section of the beam of light, since only transverse vibrations affect the eye. And here again, we need only consider circular orbits, since all others can be reduced to them. These circular rotations can take place in a clockwise or anti-clockwise direction. Likewise, the molecular electron currents in the magnet can be in the two directions. Let them be clockwise as seen by the observer; that is to say, let the pole furthest from the observer be a north-seeking pole. Then all the clockwise electrons in the flame will be retarded, and all the anti-clockwise electrons will be

accelerated, according to the laws of electro-magnetic induction. The difference in the period thus produced is, according to Lorentz—

$$t = \frac{e}{m}\frac{H}{4\pi}T^2$$

where t is the difference of periodic time, $\frac{e}{m}$ is the ratio of charge to mass of the electrons, H the magnetic field, and T the original period of all electrons constituting the original vibration. Instead of all the electrons having the same period, we shall have one set with a longer period, and the other with a shorter period. The difference of period means a difference of wave-length and a difference of refraction, and hence also a separation in the spectrum. This is the Zeeman effect as seen in the direction of the lines of force. It will be readily seen that it gave Prof. Lorentz a welcome opportunity of calculating the important ratio $\frac{e}{m}$, since all the other quantities in the above equation are known.[1]

The unexpectedly large value of the ratio gave

[1] If we put $\frac{e}{m} = 1{\cdot}9 \times 10^7$, $H = 5000$, and $T = 2 \times 10^{-15}$ we get

$$t = 1{\cdot}9 \times 10^7 \times 5000 \times 4 \times 10^{-30} \times \frac{1}{4\pi}$$
$$= 3 \times 10^{-20}$$

and $$\frac{t}{T} = \frac{1}{66000}$$

which agrees with the observations within the limits of error.

rise to various speculations; but the smallness of the mass could not be accounted for, since no mass smaller than the hydrogen atom was known at that time.

A further spectroscopic examination of the split lines showed that they consisted of circularly polarised light, the direction of rotation being in opposite directions in the two lines. A most important result was deduced from observing the direction of rotation in the two lines. Zeeman found that the electrons producing the longer wave-length were rotating clockwise, and the electrons producing the shorter and more refrangible waves were rotating anti-clockwise. This proved *that the light-bearing rotations were those of negatively charged particles only.* Indeed, we know from the laws of induction that the clockwise rotations are retarded by clockwise molecular electron currents, thus lengthening the waves and increasing the refrangibility, whereas the others are accelerated.

So much for the phenomenon as observed along the lines of magnetic force. At right angles to the lines of force a triplet is observed instead of a doublet. The two circular vibrations we have been considering are seen end-on, and, therefore, appear plane-polarised, the plane of polarisation being parallel to the lines of force, and, therefore, at right angles to the vibrations of the electrons. There is the same difference of period as before, and, there-

fore, the same separation. But in this case there are also the vibrations *along* the lines of force influencing the eye, but suffering no influence from the magnetic field, since electrons are only affected by such a field when they cross the lines of magnetic force. There being no difference of period produced in this case, the original vibration remains, and a central line appears between the other two. Being due to vibrations along the lines of force, the rays are polarised in a plane at right angles to the lines

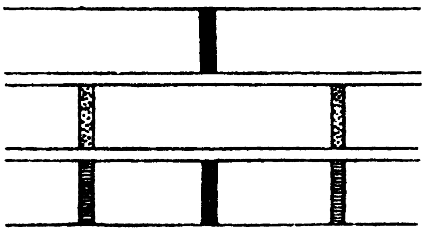

FIG. 31.

of force. In this case there can be no doubt as to the direction of vibration of particles giving rise to polarised light, and an old optical controversy, already partly decided by Hertz's experiments, is thus finally set at rest.

This is the famous Zeeman effect in its simplest form. The main phenomena are shown in the diagram (Fig. 31), where the solid line shows the ordinary D_1 line, the punctuated lines show the circularly polarised lines as seen along the lines of

force, and the shaded lines are the lines polarised in two different planes, as seen across the lines of force.

But the effect is not in reality as simple as it would appear from the above description. The very fact that there are two different sodium lines shows that the electrons revolving round the sodium atom have two different natural periods, or that each atom has two electrons revolving round it, like two satellites with different periods. But affairs are still more complicated in the spectra of the heavier metals, some of which have hundreds of spectrum lines distributed apparently at random. This means a great number of electrons attached to each atom, or perhaps to a complicated group of atoms, and so much within each other's sphere of influence that they disturb each other's motion, and superpose extra vibrations of higher frequencies upon their fundamental periods. Accordingly we find, notably in the magnetic metals, some very complicated Zeeman effects, lines being split up into four, five, seven, or even nine components. But, far from being a discouragement, this bewildering variety has been a valuable stimulus to research into the intimate structure of the chemical atom. The spectrum is, so to speak, the anatomical atlas of the chemical atom, and the index to this atlas is supplied by the Zeeman effect.

For it has been found that the lines of each element can be grouped into several series which

follow in harmonic succession, and where each series shows the same Zeeman effect in all its lines, but where the effect alters from one series to another. Apart from this, there is a mathematical analysis of the atomic vibrations yet to come, and, perhaps, before very long, we shall have definite information concerning the number of electrons circulating round the atom of some element, and concerning the manner in which these revolving electrons give rise to its complicated spectrum. We may thus arrive at a knowledge of the atomic system as precise as is, on a much larger scale, our knowledge of the motions and perturbations of the planets in the Solar System.

(b) *The Faraday Effect.*—The first magneto-optic effect discovered was that named the Faraday effect. When plane-polarised yellow light is sent through bisulphide of carbon contained in a magnetic field of 5000 units, in the direction of the lines of force, the plane of polarisation is found to have been turned through an angle of three and a half degrees for every centimetre of the liquid traversed by the beam. The sense of the rotation is contrary to the direction of the electron currents constituting the magnet. In other words, it is in the same direction as the (positive) "current" which excites the magnet.

This phenomenon admits of a simple explanation on the basis of the electron theory.

Every plane-polarised beam may be considered as consisting of two beams circularly polarised in opposite directions. The beam circularly vibrating in the direction of the electron currents of the magnet is retarded, owing to molecular induction within the liquid, and the oppositely rotating beam is accelerated. When, therefore, the two beams combine again on emerging from the liquid, the plane has been turned in the direction of the faster rotation—that is to say, in the direction opposed to the electron currents of the magnet.

This is the explanation reduced to its simplest terms. But this effect, like the Zeeman effect, shows a variety of detail. The rotation per cm. in unit magnetic field (a quantity known as Verdet's constant) changes from one substance to another, and in a few rare cases even becomes negative. Thus in carbon bisulphide, it is 0·042 minutes of arc, in water 0·012, in glass 0·02 to 0·09, while in compressed air it is 0·0003, and increases with the pressure.

To return to Drude's equation (p. 228). If the velocity of propagation is v, the refractive index n, the density of rotating electrons N, their "laxity" θ, the length of wave naturally emitted by them L, and the incident wave-length λ, we have

$$\frac{1}{v^2}=n^2=1+N\theta+\frac{N\theta L^2}{\lambda^2-L^2}.$$

This equation shows that, as the natural period

L increases, the velocity v diminishes—that is to say, if the rotating electron is retarded by magnetic force or otherwise, it transmits the incident light with a smaller velocity. Now we know that the electron is retarded when it rotates in the same direction as the electrons producing the magnetic field. Hence the circularly polarised beam transmitted by the opposite rotation will be propagated more quickly.

This supposes that λ^2 is larger than L^2. If it is not, the denominator—and, therefore, also the whole fraction—becomes negative, and the larger the natural wave-length the greater will be the velocity. This is then a case of anomalous dispersion. It occurs when L^2 is larger than λ^2—*i.e.* when the proper period of the electrons is in the infra-red. Normal dispersion occurs when the proper period of the electron is in the ultra-violet.

These considerations explain why the Faraday effect is sometimes reversed.

(*c*) *The Kerr Effect.*—Kerr discovered that plane-polarised light reflected from the polished poles of an electro-magnet is elliptically polarised. Recent experiments have shown that this is simply a special case of the Faraday effect. All reflected light penetrates for some very small depth into the reflected surface. Light reflected from iron passes through a few molecular layers, and repasses them on being reflected. These two passages

amount to a transmission through the substance of iron. Now, iron has been examined in very thin transparent films produced by cathode disintegration, and found to exert a very powerful Faraday effect. It is, therefore, not surprising that the passage of light even through the very thin films required for reflection should suffice to produce a very perceptible rotation of its plane of polarisation, more especially as the effect of both passages is in the same direction. Therein lies a fundamental difference from purely optical rotation. When a beam of light is sent through an "optically active" substance, both going and returning, its plane is not rotated at all. Transmission in one direction is compensated by transmission in the reverse direction. In magneto-optic rotation the turning of the plane of polarisation is always in the direction of the (positive) magnetising current, and hence the rotation is proportional to the number of times the beam is transmitted either way.

(*d*) *Macaluso-Corbino Effect.*—Shortly after Zeeman's discovery, two Italian physicists, Macaluso and Corbino, announced that, on transmitting a plane-polarised yellow beam through sodium vapour placed in a magnetic field, there was a strong magneto-optic rotation in the neighbourhood of the absorption bands. This follows as a matter of course from the above facts and considerations. We have already seen that when λ is very nearly

equal to L, the third term in Drude's equation becomes enormous, and hence the velocity of transmission is powerfully affected when the wave-length of the incident sodium light is nearly the same as the wave-length of the period proper to the electrons rotating in the electric field.

The whole chapter of magneto-optics, like that of the galvano-magnetic and thermo-magnetic effects to be dealt with next, still bristles with problems awaiting solution. But the electron theory has for the first time indicated the general lines along which a complete solution of outstanding questions may be looked for.

CHAPTER XIV

ELECTRICITY, HEAT, AND MAGNETISM

THE relations between electricity and heat have already been dealt with in the chapter on Thermo-electricity (p. 121). As already stated, they involve the intimate structure of the chemical elements, and are therefore less definite than most of the other electrical properties of matter. When these relations are complicated by the presence of a magnetic field, their investigation becomes by no means easier; but the more multitudinous and complicated they are, the more information do they give us concerning the hidden structure of the chemical atom and the building up of solid substances.

Let a thin metallic plate (Fig. 32) be traversed by a current from the battery B. According to the electron theory, this current consists mainly in the motion of electrons from the negative terminal to the positive terminal—*i.e.* in the direction opposed to what is conventionally called the current. The positive atoms move in the opposite direction, but

being hampered by their much greater size, the part which they contribute towards the convection of the current is insignificant.

Now let the north-seeking pole, N, of an electro-magnet be brought under the plate. Then the following four phenomena are observed.

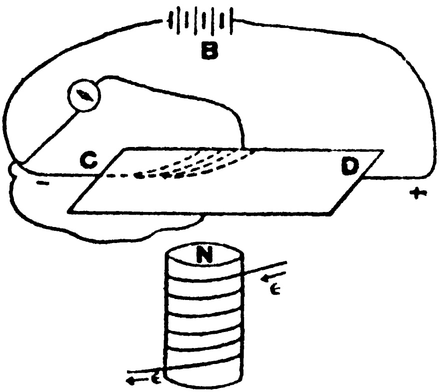

FIG. 32.

1. A difference of potential between the sides.

2. A difference of temperature between the sides of the plate.

3. A change in the electrical conductivity of the plate.

4. A change in the conductivity for heat.

If, instead of an electric current, a current of heat is directed through the plate in the same direction, as, for instance, by heating C to boiling point and keeping D cool, the same four pheno-

mena are observed. Thus we have eight galvano-magnetic and thermo-magnetic phenomena, which show an intimate connection between currents of heat, currents of electricity, and magnetism.

Now it must be stated at once that these effect vary very much, both in quantity and directio from one substance to another, and there is only one substance—bismuth—in which all the eight effects have as yet been measured. Such measurements are very difficult to carry out, on account of the many sources of error, and the decisive influence of even slight impurities. Nevertheless, some valuable rules have been discovered, and the electron theory has shown itself well able to cope with these strange phenomena.

In every case the effect is proportioned to the intensity of the electric current or heat current. This is readily understood. It is also inversely proportional to the thickness of the plate. This also is capable of a simple explanation.

The transverse effects (1) and (2) and the corresponding ones in the case of the heat current are proportional to the magnetic field. The changes of conductivity are supposed to be proportional to the square of the magnetic field, but are generally very feeble.

Transverse Effects.—The effects in bismuth may be summarised as follows: *A current of heat produces the same effects as a current of electrons.* It is

deflected by a magnetic field in the same direction as cathode rays are deflected. In a plate traversed by either a heat current or an electron current, a magnetic field increases the resistance and the

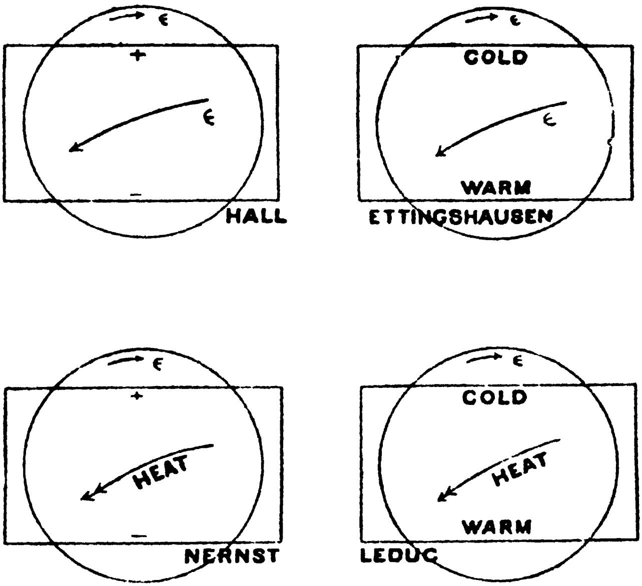

FIG. 33.

thermal conductivity. A deflection of the current of heat to one side is accompanied by a negative charge acquired by that side.

The four transverse effects are shown diagrammatically in Fig. 33, where the circles with arrowheads indicate the direction of revolution of the

electron currents which produce the magnetic field, and the long arrows represent the heat currents or electric currents.

The Hall effect in bismuth is easily explained. The electrons constituting the electron current thread their laborious way through the crystalline agglomerations of bismuth atoms, and whenever they are free to follow the electric force they dart forward in the direction of the electron current—*i.e.* from right to left. But while traversing their free path they are subject to deflection by the magnetic force. This will urge them towards the lower edge of the plate, and that edge, therefore, acquires a negative charge. The upper edge being drained of electrons, acquires a positive charge, and when the two edges are joined by a wire, a small but steady current passes through the wire.

To understand the analogous effect of a heat, current, it must be remembered that electrons are particles capable of conveying energy of motion, and that they therefore are just as capable of propagating heat as the heavier atoms are. But in most substances heat has the effect of dissociating neutral atoms. More electrons are split off and set roaming at large. There is a greater number of free electrons in unit volume of the hot metal than in unit volume of the cold metal. To equalise this difference of density, electrons diffuse from the hot

metal to the cold metal, and thus constitute an electron current which travels in the same direction as the heat current.

The Nernst effect falls under this explanation. The electrons constituting part of the heat current are deflected in the same direction as those conveying the electric current, and accumulate in the lower edge of the plate as before.

No sooner is the difference of potential established between the opposite edges than a cross-current sets in to equalise it. But the rapidity with which this process of equalisation takes place depends upon the resistance of the plate, and this is the greater the thinner it is. It is, therefore, readily understood that the Hall and Nernst effects are inversely proportional to the thickness of the plate, as stated above.

The Ettingshausen and Leduc effects are similarly explained. Though tabulated separately from the other two effects, they are really inseparable from them. The Hall and Ettingshausen effects occur together, the cold edge being positively charged and the warm edge negatively, and the Nernst and Leduc effects are similarly linked. The former are called "galvano-magnetic," and the latter "thermo-magnetic," effects. As before, the equalisation of temperatures between the opposite edges depends upon the intervening conductivity for heat.

Effects similar in every respect, but much feebler, are presented by carbon and nickel. Of the four effects described, the Hall effect was the first discovered, and it is always the easiest to observe, since no measurements of temperature are involved. Even with very thin plates and strong fields, the E.M.F. between the edges does not exceed a few thousandths of a volt. But that is well within our powers of measurement. It is by far the largest in bismuth, being 400 times greater than in nickel, which comes next in order. It is smallest in tin and lead.

The Hall effect depends upon a difference in the mobilities of the positive and negative carriers of electricity, and its existence in metals confirms the supposition that metallic conduction is carried on mainly by electrons. In liquids, the effect has been looked for in vain, for two reasons. The ions in liquids are much more thinly scattered than in metals, and their mobilities are much more nearly equal. It may be roughly estimated that in most ordinary metals the mobility of the electron exceeds that of the positive atoms 100 or 200 times. In electrolytes, no ion ever has a mobility more than about 10 times that of another ion. Hence it is clear that the Italian physicists who started in search of the Hall effect in liquids attempted practically an impossible task.

Owing to the fact that free electrons have a great tendency to condense water about them, and to form heavier negative ions, they do not act as carriers in liquids. In gases, on the other hand, they are present in large numbers, and gaseous conduction is carried on mainly by electrons and positive atoms. Hence there is quite a perceptible Hall effect in gases, especially hot gases, where the ionisation is great. The Hall effect has been proved to exist in flames without much difficulty.

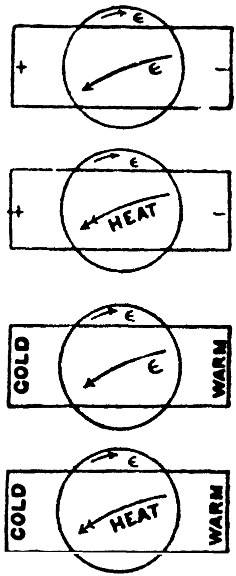

FIG. 34.

Longitudinal Effects. — The longitudinal effects are not reversed by reversing the magnetic field. They simply depend upon the state of things at the ends of the plate, and are independent of the charge or temperature of the sides.

The four effects are shown diagrammatically in Fig. 34. The electron currents are deflected in the direction in which the arrows are bent, and the heat currents are deflected in the same direction when electrons are diverted towards the lower edge of the plate, instead of making straight for the left-

hand edge; the left-hand edge will naturally be less negatively charged than before. It will, in fact, rise in positive potential, and will become comparatively more positive than the right-hand edge—that is to say, the original difference of potential is increased. The same thing would happen if the plate were made either longer or thinner. It amounts to this, then: that the magnetic field *increases the resistance* of the bismuth. The increase in a field of 10,000 units amounts to as much as one-third of the original resistance This property is so constant and reliable that it has been used for measuring the strength of magnetic fields. All that is required is a small coil of bismuth and a resistance-box. The resistance of the coil of bismuth indicates the strength of the magnetic field at the place where it happens to be. It can even be used for alternating magnetic fields; but these must not be too rapid, as otherwise the electrons have no time to get deflected out of their paths, and then the resistance remains constant.

The fourth longitudinal effect is a direct increase of the "thermal resistance," or a diminution of the conductivity for heat. The cool end of the plate becomes cooler than before as soon as the magnet is excited. It gives up less heat to the cooling water than it did before. Again *the effect is as if the plate had been lengthened. It is due, as before, to the deflection of the elec-*

trons which constitute the largest part of the heat current.

The other two effects are reciprocal effects of currents of heat and of electricity. The heat current consisting mainly of electrons, any deflection of it implies a deflection of (negative) electricity, and wherever there is an accumulation of heat there is also an accumulation of electrons—in other words, a negative electrification.

The eight effects may be combined into a single diagram (Fig. 35), where the arrows show the direction and deflection of a current, which may be either a heat current or an electron current.

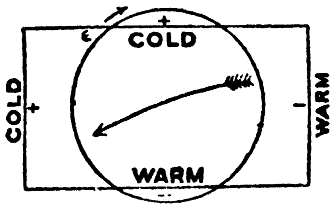

FIG. 35.

Reversed Effects.—It appears from the above details that the electron theory of metallic conduction suffices for explaining all the manifold relations between heat, electricity, and magnetism as far as bismuth is concerned. But in other metals the transverse effects are different, while the longitudinal effects are, as a rule, too small to be observed. In antimony, cobalt, and tellurium the direct (Hall and Leduc) effects are reversed, and in iron they are all reversed. This means that the laws of metallic conduction are modified by other

influences. The effects in cobalt are too small to draw any conclusions from them; but in antimony and tellurium the reversal of the two effects indicates a structure which allies those metals to the non-metallic elements. There is probably very little direct dissociation into positive atoms and electrons. The dissociation is probably more like what we have in electrolytic dissociation, each electron gathering neutral atoms round it to form heavier ions. The electron, thus weighted, has no advantage of mobility over the positive ions, and may even be inferior in mobility to the latter. That the reciprocal effects hold good shows that heat produces a splitting-off of electrons, as in bismuth.

This does not appear to be the case in iron, where it is known that heat does not produce a spontaneous evolution of free electrons. We know from the strong magnetic properties of iron that the molecules of iron are quite free to place themselves in any direction they choose, and that they do place their magnetic axes into coincidence with the axis of a magnetic field. This indicates a great freedom of the ponderable material of iron. Its treble valency also shows that one positive atom can bind several electrons. It may therefore well happen that most of the electrons are bound up with atoms, while a large number of positive atoms are roaming free, and although they have not the great mobility of the electrons, they make up for

that by their superior numbers. The same considerations will explain the reversal of the Thomson effect in iron, without having recourse to the assumption of free positive electrons, which are not indicated by any other phenomenon.

CHAPTER XV

RADIO-ACTIVITY

A NEW branch has been added to physical science within the last ten years. The phenomena of radio-activity are impossible on the basis of the older atomic theory of chemistry, though they add new proofs of the atomic structure of matter. They are largely electrical phenomena, and are quite inconsistent with the view, sometimes tentatively put forward, that electricity, like heat, is a mode of motion. The phenomena of radio-activity have confirmed the atomic structure of matter, but have abolished the dogma of the indestructibility of the atom. They have created a new department of chemistry by giving us access to the hidden recesses of the atom itself. They have also definitely established the atomic structure of electricity, substituting the indivisible and indestructible electron for the chemical atom, now no longer considered either indivisible or indestructible.

That, surely, is a tremendous revolution, a revolution for which the closing years of the nineteenth century will be for ever memorable.

This is not the place to give a detailed account

of the phenomena presented by the radio-active substances. I shall restrict myself to those phenomena which have an immediate bearing upon the electron theory.

In the course of the present sketch of the chief facts of electricity and magnetism in the light of the electron theory, I have only incidentally referred to radio-activity, preferring to establish the theory first in regions more familiar to the student. I think I can claim to have shown that in the more ordinary electric phenomena, the electron theory not only explains observed facts much better than any other theory hitherto accepted, but unifies all facts in a manner hitherto unapproached, and forms a firm and fruitful basis for further research. In proceeding, however, to radio-activity, we find that the electron theory becomes paramount and indispensable, and that it seems likely to annex the greater part of physics and the whole of chemistry.

The radio-active bodies hitherto investigated are uranium, thorium, radium, actinium, and polonium. Of these uranium and thorium were well known to chemists before the discovery of radio-activity. The others were discovered by their radio-active properties.

Radio-activity—a term invented by Madame Curie, now Professor of Chemistry at Paris University—consists in the spontaneous emission of cathode rays, canal rays, or Röntgen rays—that is to say,

of electrons, positive atoms, or ether-pulses, or of several of these at the same time.

The "positive atoms" emitted are, however, not atoms of the substance itself, but atoms of a very much lighter substance, consisting of either hydrogen or helium, probably the latter. This is the most astounding fact of the whole new range of phenomena. A well-defined chemical atom, with a characteristic spectrum of its own, splits into two, one of them an atom of a gas found in the sun and the earth, the other a substance which undergoes further decomposition by giving off more atoms of helium and electrons, and finally, perhaps, transforms itself into some other known "element."

The substance showing the greatest number of radio-active phenomena, and those in the fullest detail, is radium, discovered by Prof. and Madame Curie in 1898. It is supposed to be "descended" from uranium, and it develops into lead after six intermediate changes. Each change takes a definite time to complete itself in a given weight of the substance. As Rutherford says,[1] "There can be no doubt that in the radio-elements we are witnessing the spontaneous transformation of matter, and that the different products which arise mark the stages as halting-places in the process of transformation, where the atoms are able to exist for a

[1] "Radio-activity." By E. Rutherford: Cambridge University Press, 1905.

short time before again breaking up into new systems."

Radium is a metal closely allied to barium in its chemical properties. Its atomic weight is 225, and is only exceeded by the two radio-active elements uranium (240) and thorium (232·5). The atoms of radium are in imperfect equilibrium; but the break-up of an atom occurs so rarely that only one atom in ten thousand million breaks up every second in one gramme of pure radium. Since a gramme of pure radium contains about 4×10^{21} atoms, this means that one gramme of pure radium spontaneously breaks up 4×10^{11} of its atoms every second. The break-up of the atoms results in the projection of a positively charged helium atom with a velocity in many cases approaching the velocity of light. These charged particles are the so-called α-rays, whose nature was a mystery until their deflection by a magnet was clearly established by using a very strong field. The proportion between radium atoms present and radium disintegrated is very constant, and quite independent of heat or any other physical or chemical agent. The more the radium is disintegrated, the more slowly will the remainder disintegrate. The rate of disintegration, as well as the intensity of the α-rays, decreases, as they say, according to an exponential law. The most convenient way of stating the stability of such a body as radium is to state the time a gramme of the substance would

take to transform or disintegrate half its atoms. This time, T, is 1300 years in the case of radium. We therefore see that if pure radium has a certain radio-activity to-day, that activity will have fallen to half its present value in A.D. 3206. Meanwhile, what becomes of the products of disintegration?

The helium atoms fly off into the surrounding gas and ionise its molecules by collision. They are stopped in 3 cm. of air at atmospheric pressure; but not before they have produced about 86,000 ions for each helium atom stopped. Now a billion helium atoms do not give much helium, certainly not a measurable quantity. But that quantity becomes discoverable by spectroscopy when it is multiplied about 100 million times, and this takes about 100 million seconds, or about four years. Helium has actually been observed by Ramsay and Soddy in the spectrum of a tube containing radium after a considerable lapse of time. Moreover, helium is found occluded in all radium minerals in proportion to the amount of radium present, having been accumulated there since the radium was formed.

What remains of the radium atom after the helium atom is split off forms an atom of an inert gas resembling argon. This gas emanates from the radium mineral, and can be drawn off in a current of air and condensed at a temperature of $-150°$ C. It is called Radium Emanation. Its atomic weight

is 221, since that of the helium atom is 4, and of the radium atom 225.

The atom of emanation gives off another α-particle or helium atom, which goes to swell the amount of helium evolved direct from radium, and what then remains is no longer a gas, but a solid, which deposits itself on the walls of the vessel, and is called radium A, with an atomic weight of 217.

This change is much more rapid than that of the radium into emanation. The emanation is much more unstable than the radium itself. While radium takes 1300 years to transmute itself by half, the same process is accomplished in radium emanation in 3·8 days.

If, therefore, the emanation is drawn off into a separate tube, half of it is precipitated on the walls within 3·8 days, with evolution of helium. If now the helium and the remaining emanation is drawn off by a current of gas, we have a deposit of radium A on the walls of the tube far too minute to be seen or weighed, but discoverable by its radio-activity. For radium A also decomposes. It is soluble in strong acids, which, however, do not affect its rate of disintegration. It can be volatilised at 1000° C., but again without affecting its rate of inevitable decay. Its disintegration is accompanied by another expulsion of a helium atom—the third so far—and the remainder forms another solid deposit called radium

B. This conversion completes itself half in three minutes, and is the most rapid of all radium transformations. Radium B volatilises at 700° C. It disintegrates in turn, transforming itself by half in 21 minutes. But this transformation is not accompanied by any expulsion, and probably consists in some rearrangement of material within the atom.

The next stage is radium C, another solid substance, which volatilises at 1000° C., and makes up for the absence of rays in radium B by emitting no less than three different kinds of rays. Each atom of radium C which decomposes throws off a helium atom and an electron, and gives rise to an electromagnetic wave-pulse or Röntgen ray. Its time of half-decay, T, is 28 minutes. Radium B was discovered solely through the initial irregularity of the curves of decay of radium C. These three products, radium A, B, and C, together form the active deposit due to radium emanation. But after their disintegration, which, we have seen, does not take many minutes, they give rise to three further products, called radium D, E, and F respectively, which together form the "permanent" active deposit. T is about 40 years in the case of radium D, and the change is another rayless one. T for radium E is six days. It is non-volatile, but gives off electrons and Röntgen rays. The final product is radium F, whose T is 143 days. It gives off helium atoms (α-rays) only, and is deposited on bismuth from

solution. This radium F is an exceedingly interesting body. All its properties are identical with those of another radio-active body discovered independently by Madame Curie, and called by her "Polonium," in honour of her native country, and also by Marckwald in Germany, who found it associated with tellurium, and therefore styled it "radio-tellurium." The credit of accomplishing the long and laborious researches for tracing the parentage of polonium belongs to Rutherford, of Montreal. Here is the full pedigree:—

Radium	gives off helium atoms.		
Emanation	,,	,,	,,
Radium A	,,	,,	,,
Radium B	,,	no rays.	
Radium C	,,	helium atoms, electrons, and X-rays.	
Radium D	,,	no rays.	
Radium E	,,	electrons and X-rays.	
Radium F	,,	helium atoms.	

= Polonium = radio-tellurium.

It will be remembered that all these changes, except the evolution of helium, are undiscoverable by chemical or even spectroscopic means. The substances only identify themselves by their radiations, and the manner in which that radiation decays. The radiations may be observed in different ways; but the most convenient method is by the ionisation of air, whereby a delicate electroscope is dis-

charged. For aught we know, many more changes may be continually going on, not only in radio-active bodies, but in ordinary matter. The α-rays or helium atoms cease to produce ionisation when their velocity falls below the enormous figure of 10^9 cm. per second, or one-thirtieth of that of light. Consequently, it is quite possible that all matter may be gradually disintegrating, but not with the explosive violence of the radio-active bodies, and therefore unperceived. Many indications go to show that polonium itself eventually changes into either lead or bismuth.

Uranium, thorium, and actinium show a somewhat similar life-history; but in their case the first product formed is not an emanation, but a solid. Uranium gives rise to "Uranium X," and any further change is at present unknown. Uranium takes about 600 million years to transform itself by half. Each atom which disintegrates gives off an α-particle (helium atom), and leaves behind an atom of a new substance, which disintegrates much more easily. This new substance is called uranium X. It was for some time considered to be the sole active constituent of uranium. Its discovery is described by Rutherford as follows:—

"The experiments of Mme. Curie show that the radio-activity of uranium and radium is an atomic phenomenon. The activity of any uranium compound depends only on the amount of that

element present, and is unaffected by its chemical combination with other substances, and is not appreciably affected by wide variations of temperature. It would thus seem probable, since the activity of uranium is a specific property of the element, that the activity could not be separated from it by chemical agencies. In 1900, however, Sir William Crookes showed that, by a single chemical operation, uranium could be obtained photographically inactive, while the whole of the activity could be concentrated in a small residue free from uranium. This residue, to which he gave the name of 'Ur X,' was many hundred times more active photographically, weight for weight, than the uranium from which it had been separated. The method employed for this separation was to precipitate a solution of the uranium with ammonium carbonate. On dissolving the precipitate in an excess of the reagent a light precipitate remained behind. This was filtered, and constituted the Ur X. The active substance Ur X was probably present in a very small quantity, mixed with impurities derived from the uranium. No new lines were observed in the spectrum. A partial separation of the activity of uranium was also effected by another method. Crystallised uranium nitrate was dissolved in ether, when it was found that the uranium divided itself between the ether and water present in two unequal fractions. The small part

dissolved in the water layer was found to contain practically all the activity when examined by the photographic method, while the other fraction was almost inactive. These results, taken by themselves, pointed very strongly to the conclusion that the activity of uranium was not due to the element itself, but to some other substance associated with it, which had distinct chemical properties.

"Results of a similar character were observed by Becquerel. It was found that barium could be made photographically very active by adding barium chloride to the uranium solution and precipitating the barium as sulphate. By a succession of precipitations the uranium was rendered photographically almost inactive, while the barium was strongly active.

"The inactive uranium and the active barium were laid aside; but, on examining them a year later, it was found that the uranium had completely regained its activity, while that of the barium had completely disappeared. The loss of activity of uranium was thus only temporary in character."

The obvious explanation of this peculiar behaviour was that uranium continually evolves some substance much more active than itself, which can be chemically separated from it. This new substance, Uranium X, decays to half-value in 22 days, instead of hundreds of millions of years. The original uranium can only be identified by a feeble

radio-activity consisting in the expulsion of helium atoms.

Thorium and actinium give rise to similar products called thorium X and actinium X respectively. From these a gas or emanation is developed, which, however, is extremely unstable and takes only a few seconds to decay by half. Thorium emanation gives rise to two successive decomposition products called thorium A and thorium B. They form a deposit on bodies and are concentrated on the cathode in an electric field. Thorium A is more volatile than thorium B.

Lastly, actinium emanation gives rise to actinium A and actinium B, which are deposited on bodies concentrated on the cathode in an electric field, and are soluble in ammonia and strong acids: they are volatilised at the boiling-point of water. Actinium A can be separated from actinium B by electrolysis. Both thorium B and actinium B emit three sorts of rays, while their "parents" emit none. Their life period counts by minutes.

These are all the radio-active bodies and disintegration products hitherto known. The list will, no doubt, soon be extended—possibly into the region of well-known bodies like lead, mercury, and gold. Research is busy with the momentous question as to whether any artificial method can accelerate or retard this process of disintegration. This is a question not at all easy of solution. The

effect of heat may not be to accelerate or retard decay, but to make the presence or absence of a given substance either more or less evident to us, as they differ in melting-point or volatility. The fact that uranium shows the same activity in liquid air and at ordinary temperatures goes to show that the activity resides within the atom itself. P. Curie also found that the luminosity of radium and its power of exciting fluorescence in bodies were retained at the temperature of liquid air. If a radium compound is heated in an open vessel, it is found that the activity, measured by the α-rays, falls to about 25 per cent. of its original value. This, however, is explained by Rutherford as not being due to a change in the radio-activity, but to the release of the radium-emanation, which is stored in the radium. No alteration is observed if the radium is heated in a closed vessel, from which none of the radio-active products are able to escape.

Of all the radio-active materials mentioned, radium possesses the most striking properties. It is two million times more active than uranium, and a few milligrammes suffice to produce strong photographic action, to discharge electroscopes, to give a brilliant luminosity to a fluorescent screen, and to produce dangerous and painful effects on the skin. All radium compounds shine in the dark, especially when dry. A small quantity has been known to give light enough to read by in a

dark room, though that practice is by no means to be recommended. But it is not the purest preparations of radium salt that give most light. A strong admixture of barium increases the luminosity, which is by no means so well-defined a property as the radio-activity.

A radium preparation — usually a few milligrammes of radium bromide mounted between thin glass plates—gives out α-rays, β-rays (which are identical with projected electrons and cathode rays), and the so-called γ-rays, or ether pulses, which do not consist of any kind of projected particles. The α-rays are, as mentioned above, in all probability atoms of helium, and are, therefore, very much bulkier than electrons. The latter have, indeed, a hundred times more power of penetration than the former, and can pass through a sheet of aluminium half a millimetre thick. But this power of penetration is surpassed over a hundred times by the γ-rays, the most penetrating radiation known, which can pierce through 3 in. of aluminium and ½ in. of lead!

That these three radiations are simultaneously emitted by the radium preparation is readily understood if we consider that the preparation contains not only the original radium, which slowly evolves helium atoms, but also the emanation and the active deposits, including radium C, which gives off all those classes of rays.

The three radiations are readily separated by a strong magnetic field. If a thin line of radium is placed along the lines of force in a narrow horizontal trough, the γ-rays shoot straight upwards, while the β-rays, being electrons, are bent over to one side, and the α-rays deflected to a very much slighter extent towards the other side. Those electrons that are projected in a line at right angles to the trough describe complete circles if free to do so, and it is possible to make them record their presence on a photographic film at any point in the circumference. Such tracings of the path of the electrons projected by radium are capable of great delicacy. Kaufmann succeeded in showing both their magnetic and electric deflection simultaneously, and was thus enabled to determine the ratio $\frac{e}{m}$ of the charge to the mass. It turned out to be exactly the same as the value deduced from cathode rays and from the Zeeman effect, and thus furnished a striking proof of the fundamental importance and identity of electrons.

A remarkable phenomenon, first observed by Curie, is that radium maintains itself steadily at a temperature about 3° above its surroundings. This heat is most due to the expulsion of helium atoms. It has been calculated that 1 gramme of radium gives off 100 gramme-calories of heat per hour. This would mean that during its whole "life" it

would give off $1 \cdot 6 \times 10^9$ gramme-calories, or about a million times more energy, weight for weight, than was hitherto known in any chemical reaction. This fact enables us to realise the vast forces which may become available once we can control the rate of disintegration of the atom. It confirms what was said in the initial chapters with regard to the vast stores of energy perceptible in the most elementary electrical phenomena as soon as we deal with them on a molecular scale.

CHAPTER XVI

CONSTITUTION OF THE ELECTRON

We have seen that practically all the known phenomena of electricity and magnetism can be explained by assuming that—

1. The electric current consists in the motion of very small electric particles called electrons, having a definite and constant charge, and a definite mass which is constant, but becomes larger at very high velocities.

2. These electrons are usually associated with atoms of ordinary matter, round which they describe circular or elliptical orbits, with periods approaching those of visible light-waves.

3. That there is a force of attraction between the atoms and the electrons belonging to it which continues to act when they are separated, but rapidly decreases with increasing distance.

4. That atoms deprived of electrons repel each other.

5. That electrons mutually repel each other.

6. That electrons moving side by side through the ether attract each other with a force propor-

tional to their speed, and inversely proportional to the square of their distance apart.

7. A change of momentum of an electron produces a change of momentum in every other electron in the opposite direction.

These assumptions and their corollaries embrace nearly all the facts hitherto accumulated. They are few in number—surprisingly few considering the vast array of facts they cover—and certainly fewer than those which form the basis of any of the older theories. But the human mind is never satisfied to take things, even simple things, for granted. These things must be "explained" in their turn—that is to say, they must be reduced to other and fewer and more familiar ideas. Such curiosity is legitimate so long as there are any facts remaining unaccounted for. But if it should be found that all facts are satisfactorily explained by the assumptions of the electron theory, then the science of electricity will be complete, and further research into the cause and reasonableness of the fundamental assumptions will add nothing new to electrical science. They may add to our knowledge, indeed; but that new knowledge will constitute a new science. This is made evident by a glance at mathematical astronomy. All its facts are accounted for by Newton's law of gravitation, which states that two heavenly bodies attract each other with a force proportional to the product

of their masses, and inversely proportional to the square of their distance apart. Further research into the nature of gravitational force will not amplify mathematical astronomy, nor will it enable us to predict astronomical events with greater accuracy than before. If, however, the law of gravitation should be found to be subject to exceptions, the theory will have to be recast, and this will mean, not a retrogression, but an advance towards new and more general truths.

As J. J. Thomson says, the electron is at present better known than the atom. It is likely, therefore, that an electron theory of the chemical atom will shortly come into being. Such a theory is made necessary by the facts of radio-activity where atoms are found throwing off electrons and positive particles. These electrons and positive particles must therefore have been constituents of the atom.

The atom, with its detachable electrons, is sometimes compared to the solar system. The analogy is somewhat far-reaching, and deserves to be pointed out, if only to assist the memory and the imagination.

If the solar system is an atom on a large scale the sun must be regarded as the positive nucleus and the planets as the electrons. It is actually found that the sun has a positive charge, and the earth a negative charge. But these charges are comparatively infinitesimal, and do not perceptibly

influence the force between them. In this point, therefore, the analogy fails. On the other hand, the ratio of the masses is very instructive. That of Jupiter is about one-thousandth of that of the sun, and approaches the mass of an electron in comparison with a hydrogen atom. The mass of the earth is $\frac{1}{324000}$ of that of the sun, and this ratio is nearly the same as that of an electron to the atoms of the heavy metals. We may say, therefore, that in the solar system we have examples of the various actual ratios of mass as between an electron and its positive nucleus, though in the case of atoms it is the atoms themselves, and not the electrons, which vary in mass.

The solar system may be regarded as a magnetic molecule. The charge of the earth is at the very least 25 million coulombs or "armies" of electrons. This charge passes round the sun once every year, so that the current represented by the earth's motion is 25 million coulombs per annum, or just about 1 ampère (0·1 "electro-magnetic" unit of current). The magnetic moment (see p. 167) of the system sun-earth may be obtained by multiplying the current by the area round which it circulates. The area of the earth's orbit is about 10^{27} square centimetres, so that the magnetic moment of the system sun-earth is 10^{26} c.g.s. units. This moment is too small to exert any measurable effect outside

the solar system, not to speak of influencing the orientation of the planetary orbits of other stars. Hence we see, as before, that magnetic and electric forces play no appreciable part in the motions of the heavenly bodies.

It may well be, however, that the sun's positive electric charge just balances the negative charges of the planets, in which case the solar system would represent a neutral atom of matter. If, under such circumstances, another neutral solar system were to approach ours sufficiently closely to entice Neptune from its allegiance to our own sun, we should have an illustration of two atoms combining, and then separating with opposite charges, our solar system being positively charged, and the foreign system negatively, having captured one "electron," Neptune, from us. Thus we should represent, say, a mercury atom, and the foreign solar system, say, a chlorine atom.

As matters stand, the solar systems of the visible universe do not seem to approach together so closely as to interfere with each other's planets. The visible universe thus represents a gas rather than a liquid or solid, except that portion called the Milky Way, which appears to have a consistency capable of giving it a metallic appearance if it could, by some magic means, be reduced to tangible dimensions.

The visible stars number quite a thousand million.

Now, the smallest object visible in a microscope contains at least a hundred million atoms. We may take it for granted, then, that the visible universe, whose outer edge is the Milky Way, if reduced in the same proportion that an electron bears to the earth, would resemble something rather like a human blood corpuscle, and would contain about the same number of atoms.

A blood corpuscle is too small to observe individually its electric and magnetic properties, not to speak of examining the properties of its individual atoms and electrons. A large number of universes would have to be taken together, and the results would be average values. If we can imagine a giant of this new Brobdingnag endeavouring to arrive at some measurements of the masses, velocities, and electric charges of the stars and planets—"atoms" and "electrons" he would call them—he might very well find the same average value for each million of them which he might pick out at random. He might find that the ratio of the charge to the mass of each detachable planet was the same, and that the charge of each planet approached a standard value within the limits of his powers of measurement. He would naturally arrive at the same conclusion as we do with regard to the electrons—viz. that they are absolutely constant and equal bodies, constituting the physical units and vehicles of electricity.

Further, our giant might be able to sort the various solar systems according to their masses, and establish certain "chemical" affinities between systems of different mass. He might find that the masses, which he would call "atomic weights," showed a certain constancy, and a determining influence upon the affinity and chemical characteristics, and would thus be led to discover a large-scale "periodic law." He might, by compression or chemical treatment, bring the solar systems closer together, and enable a certain number of planets to roam at large among the fixed stars. He would thus have produced a "conductor." Finally, he might succeed in turning the ecliptics of the various solar systems into the same plane, and thus would produce a "magnet" of stupendous magnitude.

We thus see that much insight into molecular physics may be gained by considerations of astronomical phenomena happening on a much larger scale.

The scale by which we must reduce the visible universe to get it down to microscopic dimensions is 10^{22} to 1. The radius of the solar system is, roughly, 10^{14} cm. This, on dividing by 10^{22}, becomes 10^{-8} cm., the radius of an atom. Neptune, one of the most "detachable" planets we have, may be likened to a detachable electron. Its radius is about 10^{9} cm., and this, reduced in the

same proportion, becomes 10^{-13} cm., the radius of an electron. The mass of Neptune bears about the same ratio to that of the solar system as that of an electron bears to that of a lithium or oxygen atom, so that the analogy still holds good. The distance between the sun and the nearest fixed star is about 10^{18} cm., and this, divided by 10^{22}, becomes 10^{-4} cm., or 0·001 mm., which is the mean free path of a molecule of air on a high mountain.

If, besides reducing the linear dimensions from 10^{22} to 1, we suppose the present velocities of the heavenly bodies to be maintained, we obtain some very interesting and suggestive results. Since Neptune takes some 220 years to revolve once round the sun, its "frequency" of revolution (*i.e.* revolutions per second) is $1{\cdot}5 \times 10^{-10}$. Since the path is reduced 10^{22} times, the frequency of describing it will be increased in the same proportion, and will become $1{\cdot}5 \times 10^{12}$. This is the frequency of some infra-red waves of light. The frequency of the planet Mercury will become $1{\cdot}25 \times 10^{15}$, which lies in the ultra-violet. All the other planets will produce spectrum lines intermediate between these—*i.e.* lying in the visible spectrum. The asteroids will produce a broad band instead of a line, and there will be certain extra lines due to perturbations of the planets by each other. *The solar system will, therefore, present a spectrum much resembling the spectrum of a chemical element.* This is a striking feature

of the analogy between an atom and a planetary system.

We may also, of course, reverse the process by taking the Lilliput world of the atom and the electron, and enlarging it by the factor 10^{22}, leaving all its velocities as they were. An atom of, say, oxygen would thus become of the same size as the solar system, and its two detachable electrons would closely resemble Uranus and Neptune as regards size, distance from the sun, and period of revolution. One of the electrons more closely bound up with the atom, and assisting in producing the phenomena of magnetism and radiation, but not of conduction, might resemble the earth in size, and distance from the sun, and might revolve round the latter in one sidereal year. We naturally expect an electron, when enlarged to the size of the earth, to be a perfectly smooth sphere. At least, so we are accustomed to find it described. But such a sphere is, in reality, absolutely inconceivable; nor is it necessary to imagine it to be so. An electron may have a structure resembling that of the earth in every particular, and yet not only could that make no difference to its electrical or astronomical properties, but the fact of its having such a structure would remain for ever unknown to us, considering the scale of phenomena which are accessible to our senses. We may therefore, without in the least interfering with the efficiency of the electron as a universal vehicle of

electrical manifestations, imagine it to be a veritable microcosm, a world in which life might not very materially differ from life on our earth. Indeed, considering that time and space would be reduced in the same constant and uniform proportion, it is doubtful whether our present instruments, thus suddenly transformed, would be able to indicate the occurrence of any fundamental change. This is but another illustration of the well-known principle that size and length of time are purely relative, and depend upon comparison with standards. If all dimensions, including the standards, were reduced in the same proportion, or if all things were accelerated or retarded in the same proportion, we should be absolutely unaware that anything had happened.

On the other hand, if any intelligent being could be transferred from the microcosm to our present world, and could keep up some connection with the microcosm, his busy life here would appear to the inhabitants of the microcosm to be a changeless eternity, since any change measurable by them would take millions of their years to accomplish itself.

We here enter upon the region of pure speculation, and it is not the function of a scientific work to deal with occult problems of that kind. But since the electron theory promises to guide us further into the mysteries of matter than anything attempted hitherto, it is necessary to discuss the

general prospect even cursorily. To sum up, we find in the fruitful and suggestive astronomico-chemical analogy a boundless vista of worlds within worlds, which, while rightly preventing us from setting a limit to the multiplicity of possible phenomena, comforts us with the reflection that for our purposes, and as far as our present senses are concerned, the multiplicity of phenomena has an absolute limit, which makes it possible to look forward to the eventual formulation of a theory embracing all phenomena accessible to our senses.

CHAPTER XVII

DIMENSIONS OF ELECTRICAL QUANTITIES

THE discovery that electricity has an atomic structure, that its carriers are discrete particles, brings the desirability of recasting our dimensional formulæ into renewed prominence. We find that electricity is as fundamental as mass, perhaps, indeed, more fundamental, and all indications point to the advantage of recognising electricity as a fundamental natural quantity. The other fundamental quantities so far recognised are length, mass, and time. They are called fundamental quantities because, while none of them can be measured in terms of the rest of them, the three quantities are capable of measuring other more complex quantities. Thus, we require no fundamental unit for velocity. We measure it in terms of our units of space and time, as cm. per second, or miles per hour. Neither do we require a separate fundamental unit for work, which can be expressed in foot-pounds or horse-power-hours. There is nothing to prevent us adopting a special unit for it, such as the erg; but this unit is not fundamental, as it can be reduced to mass, space, and time.

A formula which expresses the manner in which the three fundamental units enter into the composition of derived units is called a dimensional formula. These formulæ are very useful in giving us an analysis of the structure of a physical quantity, much as chemical formulæ reveal to us the structure of the chemical molecule. They are also useful for converting quantities from one system of measurement to another.

The fundamental quantities mass, length, and time are denoted by the symbols M, L, and T respectively. Of these, L is the most fundamental of all, since M and T are often measured as lengths on a scale referred to the dimensions of the earth. T is referred to the time of rotation of the earth about its axis. M is referred to L and T by the stipulation that the unit of mass is the mass of water contained in one cubic centimetre when at its greatest density. Thus we see that size and rotation of the earth as a whole give us our standards of space and time, and that a peculiar chemical substance—water—gives us the standard of mass. This again illustrates the less fundamental character of mass.

The measurement of an area requires two independent measurements of length, the results being multiplied together. Denoting each measurement by L, the measurement of an area may, therefore, be denoted by L^2, and the measurement of a volume

by L^3. The last formula also indicates that when the linear scale is altered in any ratio, the numerical result will be altered in the third power of that ratio, since the three results of the separate measurements of length are affected in the same manner.

The measurement of a velocity involves the simultaneous measurement of a length and a time. The velocity increases with the length, and decreases with the time taken to describe it. The dimensional formula of velocity is, therefore, $\frac{L}{T}$, or, as it is more usually written, LT^{-1}. In measuring acceleration, we measure the velocity acquired in a certain time. There are, therefore, two independent measures of time involved in the same determination, and the dimensional formula becomes LT^{-2}. Force is measured by the mass moved and the velocity it acquires in unit time. Its dimensional formula is MLT^{-2}. Work or energy, measured by the product of force into distance, is represented by ML^2T^{-2}, and so on.

It has sometimes been proposed to eliminate M from the dimensional calculus and to reduce it to L and T, as these are more fundamental. This can be done as soon as we can obtain an equation from which M may be evolved in terms of L and T. For this purpose we must find another permanent and universal property of mass besides that of always acquiring the same velocity under a given impulse. If, for instance, all bodies were equally dense, mass

would become identical with volume, and its furmula would be L^3. This, of course, is not by any means the case. But there is another universal property of mass, discovered by Newton. It is that the force of attraction between two masses is directly proportional to the product of the masses and inversely proportional to the square of the distance between them. This force may therefore be put $= \frac{MM}{L^2}$ or $M^2 L^{-2}$. A force, as we may have seen above, has the dimensional formula $M L T^{-2}$. Hence we have

$$M L T^{-2} = M^2 L^{-2}$$

which cannot be true unless either (*a*) some other quantity, such as the density of the ether, is left out of account, or (*b*) mass is expressible in terms of L and T. For it is obvious that the dimensional formulæ must be the same on both sides of the equation. We can never equate a length with a time, since they are two essentially different quantities. It would be like saying, for instance, that three horses equal three dogs. Adopting the alternative (*b*), and dividing both sides by M, we obtain

$$L T^{-2} = M L^{-2} \text{ or } M = L^3 T^{-2}$$

which may be regarded as the product of a length into the square of a velocity. Since, however, we are as yet in entire ignorance of what that supposed velocity and length may signify, the gain is trifling. We might, indeed, measure the masses of different

bullets of the same size by the depth to which they penetrate into wood when fired with a given velocity; but the new method would be clumsy in comparison with the usual weighing methods. Besides, the discarding of M would make us lose a definite and useful physical conception which appeals directly to our muscular sense.

Now, all the arguments in favour of retaining mass as a fundamental quantity also tell in favour of recognising electric quantity as a fundamental quantity. And it has a natural unit, the electron, of a much more prevailing and universal kind.

Electric quantity may be measured by any one of the many sets of phenomena in which the amount of it present plays a decisive part.

We have already described the two chief systems of measuring electricity, one derived from electrostatic repulsion (p. 38), and the other from electrodynamic or magnetic force (p. 148). To these may be added the chemical system, which furnishes the most accurate method, though usually based upon the electro-magnetic system. The electrostatic system derives its unit of electricity from the repulsion of two quantities of the same sign placed at unit distance apart. This is like deducing the unit of mass from its gravitational attraction. The equation is

$$M L T^{-2} = E^2 L^{-2}$$

where E is the quantity of electricity. If we wish

to reduce E to M, L, and T, we must solve the above equation for E. We obtain

$$E^2 = M\,L^3\,T^{-2} \text{ and } E = M^{\frac{1}{2}}\,L^{\frac{3}{2}}\,T^{-1}.$$

This dimensional formula for E is very complicated, and its interpretation is made difficult owing to the fractional index of M, which seems irrational. And even if we adopt it we do not know what properties of the medium we are leaving out of account. Besides, we obtain a different dimensional formula for E when we deduce it from some other property, such as magnetic force. It is, therefore, more advisable to consider quantity of electricity a fundamental quantity, and to refer it to the electron as a standard, or to any of its measurable effects. By doing this we obtain a uniform, simple, and rational system of dimensional formulæ, as will be seen in what follows.

The fundamental units are M mass, L length T time, and E electricity. We obtain the following dimensional formulæ:—

Electric quantity, E.

Surface density of electricity, or quantity of electricity per sq. cm., $E\,L^{-2}$.

Electric current, quantity of electricity passing a given surface in one second, $E\,T^{-1}$.

Current density, current per sq. cm. of section across conductor, $E\,T^{-1}\,L^{-2}$.

Electric force, same formula as force, $M\,L\,T^{-2}$.

Electrostatic field, force exerted on unit quantity of electricity, $M\ L\ T^{-2}\ E^{-1}$.

Electric potential, work done on unit quantity, $M\ L^2\ T^{-2}\ E^{-1}$.

Dielectric constant, (density of electrons) × (displacement in unit field), $E^2\ M^{-1}\ L^{-3}\ T^2$.

Resistance, by Ohm's law, E.M.F. / current, $M\ L^2\ T^{-1}\ E^{-2}$.

Resistivity or specific resistance, resistance of 1 cm. cube, $M\ L^3\ T^{-1}\ E^{-2}$.

Conductivity (specific), inverse of resistivity, $M^{-1}\ L^{-3}\ T\ E^2$.

This last admits of a simple interpretation in accordance with the electron theory (see p. 108). We may write it

$$\frac{E}{L^3} \cdot \frac{L}{T} \cdot \frac{E}{M\ L\ T^{-2}}.$$

Or

$$(\text{electrons per c.c.}) \times (\text{velocity of electrons}) \times \left(\frac{1}{\text{field}}\right).$$

That is to say, the specific conductivity is measured by the number of free electrons per cubic cm., multiplied by the steady speed which each free electron acquires in a unit field.

We also get the following magnetic formulæ :—

Magnetic moment, current multiplied by area round which it circulates, $E\ T^{-1}\ L^2$.

Magnetic pole-strength, magnetic moment per unit length, $E\ T^{-1}\ L$.

Magnetic force, same as force.

Magnetic potential, work per unit magnet pole, $M^{-1} L T^{-1} E^{-1}$.

Magnetic field, force per unit magnet pole, $E^{-1} M T^{-1}$.

Intensity of magnetisation, magnetic moment per unit volume, $E T^{-1} L^{-1}$, which means the current circulating round unit length of the magnet.

Strength of a magnetic shell, $E T^{-1}$ (= current circulating round it).

Magnetic flux, field multiplied by area, $E^{-1} M T^{-1} L^2$.

Magnetic susceptibility, intensity of magnetisation acquired in unit field, $E^2 M^{-1} L^{-1}$.

Finally, for *inductance*, or the coefficient of self-induction, being the E.M.F. induced in a circuit by unit charge of current per second, we obtain

$$M L^2 T^{-2} E^{-1} \div \frac{E T^{-1}}{T}, \text{ or } M L^2 E^{-2}.$$

The above dimensional formulæ exhibit at a glance the structure and derivation of the various electric and magnetic quantities, and their connection with the unit of electricity.

Practical Units.—The natural unit of electricity is the electron. But it is so excessively small that it would be necessary to adopt a large multiple of it in practice—say, a trillion electrons, or 0·112 coulomb—sufficient to pass 0·126 milligrammes of silver through an electrolytic cell. This, however, is at present impossible, since the charge of an electron

is not known with sufficient accuracy. In any case, it would be unwise to dislocate electrical engineering by displacing the present units unless some very great advantage would accrue therefrom. The practical unit of electricity is the coulomb, which contains 8·79 trillion electrons. This unit I have sometimes called an "army" of electrons, not in order to displace the word coulomb, but to emphasise the atomic structure of electricity, and also to distinguish it from the much smaller electrostatic unit or "company" (see p. 38). The ratio of the electro-magnetic unit (10 "armies") to the "company" is 3×10^{10}, or the figure representing the velocity of light. The magnetic attraction between two electrons moving side by side through the ether just balances their electrostatic repulsion when their velocity reaches that figure.

The practical unit of current strength is the *ampère*, consisting in the passage of one coulomb per second through any cross-section of the conductor. If a current of one ampère is sent through an electrolytic cell or voltameter consisting of silver electrodes immersed in a solution of silver nitrate, the current deposits 1·118 milligrammes of silver per second. This is the legal definition of current strength. It may also be arrived at through magnetic attraction (see p. 153), and that is how the unit of current was originally fixed. But the "electro-magnetic" unit of current is ten times the value of the ampère.

The next most important unit is that of difference of potential. To bring a quantity of electricity from a point at low potential to a point at high potential requires an expenditure of work. This work per unit quantity measures the difference of potential between the two points. We might define unit difference of potential as existing between two points when it requires one "erg" of work to bring one "company" or electrostatic unit of electrons from one to the other. This is the electrostatic unit of difference of potential. The practical unit is the *volt*, which is $\frac{1}{300}$th part of this. To take one coulomb through a difference of potential of one volt requires an expenditure of 10 million ergs, a quantity which has been called one "*joule*," after Joule, the discoverer of the law of heating in current-bearing wires. Conversely, when one coulomb falls through one volt, one joule of work may be derived from it. As a rule, it is represented by the heat in the wire, generated by the stoppages of the electrons.

The most obvious way of defining conductivity would be to ascribe unit conductivity to a substance containing one free electron per cubic cm., capable of acquiring a steady speed of one cm. per second, under the influence of a field of one volt per cm., or to stipulate that in such a field one electron per second should pass through every square cm. of the cross-section. But in practice the conductivity is derived from

the resistance, and this is derived from the current and voltage. A conductor has a unit resistance of one "*ohm*" if a current of one ampère flows through it on applying a difference of potential of one volt to its ends.

The work done by a current is measured in joules. The rate of work or "power" is measured by the product of current and voltage, the unit being the *watt*, consisting of one joule per second. Many practical electricians measure the work in watt-seconds or kilowatt-hours rather than in joules. One kilowatt-hour is 3,600,000 joules, or $3 \cdot 6 \times 10^{13}$ ergs.

It has already been stated (p. 168) that unit magnetic pole is possessed by a long thin magnet of 1 sq. cm. sectional area if the current circulating round it amounts to one electro-magnetic unit (= 10 ampères) per cm. length. In this case the practical unit (the ampère) is not adopted, and the same may be said of the other magnetic quantities, which were originally based upon the repulsion between two similar magnet poles. The most important of these are the magnetic moment (length multiplied by pole strength), the magnetic field (force per unit pole), intensity of magnetisation (magnetic moment per unit volume), and the magnetic susceptibility (magnetisation in unit field). The magnetic "permeability" is the total field existing in the interior of a substance when immersed in

unit field. It is measured by $1 + 4\pi K$, where K is the magnetic susceptibility. The "induction" B is the product of the permeability and the field strength. It represents the actual internal magnetic field of the substance.

This magnetic "induction" must be carefully distinguished from the electro-magnetic induction which gives rise to induced currents, and also from the electrostatic induction or "influence," which gives rise to charges in bodies when brought into an electric field. It is unfortunate that this word has acquired three different meanings.

When a current through a conductor changes, the inertia of the moving electrons, whether due to their own motion or to the reaction of surrounding electrons, represents a store of energy which is expended in resisting the change, and this store of energy per unit quantity in motion may be measured in volts. When the current either decreases or increases at the rate of one ampère per second, and the E.M.F. thus induced in the circuit is one volt, the conductor is said to have unit inductance. This unit of inductance is called one henry. It is 10^9 times the unit derived from theoretical considerations of the E.M.F. induced in a conductor traversed by lines of force, where the inductance is defined as the number of lines of force added to or subtracted from those traversing the circuit owing to the change of current (see p. 189).

The development of electrical science has suffered much by the existence of three different systems of electrical units, called the electrostatic, electromagnetic, and the practical units respectively. This multiplicity of systems was due to ignorance as to the real nature of magnetism, and to the prevalence of false analogies between electric and magnetic phenomena. We now see that magnetism is reducible to the revolution of electrons. It has sometimes been urged as an objection to this view that there would have to be some gyroscopic action due to the innumerable minute molecular gyroscopes constituted by the revolving electrons. But this objection leaves out of account the extreme shortness of the period of revolution, a shortness which enables the electron to follow a rotation much as a high-frequency galvanometer needle gives a dead-beat reading.

The electron theory, with its logical corollary—the recognition of electricity as a fundamental quantity—gives a consistent and comprehensive view of all the facts of electricity and magnetism hitherto accumulated. Within the next few years we shall, no doubt, witness its application to every detail of electrical science.

APPENDIX

RECENT PROGRESS

1. *Application of Centrifugal Force to Electrons.*—A curious experiment has been tried by E. F. Nichols, embodying an attempt to produce an electric current by centrifugal force. His idea was that if a disc of metal is spun rapidly about its centre the centrifugal force developed will force any loose electrons or positive atoms to the rim, and give the rim a negative or positive charge, which will subsist as long as the speed is maintained. He drove an aluminium disc 10 cm. in radius at a speed of 100 revolutions per second, and connected the terminals of a delicate electrometer with its centre and rim respectively. The effect, if it existed, was too small to be observed. It is hoped the attempt will be repeated on a larger scale. (See *Electrician* for October 19, 1906.)

2. *Utilisation of Earth's Potential.*—The estimated potential of the earth is -300 million volts (see p. 70). This estimate is confirmed by recent researches on atmospheric potential, and may be taken as approximately correct. A. Breydel has recently proposed to utilise this enormous store of energy by connecting different levels above and below the earth's surface, and generating electric currents by means of the difference of potential thus secured. This difference of potential amounts to some 64 volts per yard. Many balloon explosions, and explosions in mines,

are probably due to this cause. The difficulty in the way of practical working would lie in the uncertain influence of the weather conditions. These often modify and even reverse the potential gradient above the earth's surface. (See *Bulletin Mensuel de la Société Belge d'Électriciens*, No. 23, September 1906).

3. *Electrons and Spectrum Lines.*—In a paper on "Electrical Vibrations and the Constitution of the Atom" (*Philosophical Magazine*, January 1906), Lord Rayleigh discusses the various theories of the mechanism of radiation. The "sphere of positive electrification" assumed by Kelvin and Thomson to form the atomic nucleus is imagined for the purpose of enabling electrons to revolve with constant frequency, since the attraction exerted upon the electron by the containing sphere is proportional to its distance from the centre. This would give something like the observed fixity of the spectrum lines. But this fixity is only observed in glowing gases, not in glowing solids or liquids. If the electrons really revolved within the mysterious sphere of positive electrification, there is no reason why they should not give a sharp line spectrum even in the solid state. In the gaseous state, on the other hand, the collisions of atoms are very rare as measured by the number of revolutions—about one collision every 100,000 revolutions—so that between the collisions the spectrum line would be undisturbed. But here another source of disturbance must be considered. The revolving electron emits energy at the expense of its own velocity, the energy varying as the fourth power of the frequency. The loss of speed will render the position of the electron in its orbit unstable, just as that of the earth would be if it were retarded. But such retardation would not make itself felt for 100,000 revolutions at all

events, even of luminous frequencies. We thus have a steady state for 100,000 revolutions or so, and a catastrophe of some kind at the end, resulting perhaps in the total extinction of the luminous radiation. The effect in the spectroscope would be a steady and sharp line, owing to the frequency being furnished by a vast number of electrons simultaneously, the great majority of which have the standard frequency. It remains to be explained how it is that the elements always give rise to certain characteristic orbits. This is a matter which concerns the intimate structure of the atomic nucleus, and though J. J. Thomson has made an interesting attempt to build it up on the basis of stable rings of electrons, the theory of atomic constitution is only in its infancy.

Lord Rayleigh says: "A partial escape from these difficulties might be found in regarding actual spectrum lines as due to *difference tones* arising from primaries of much higher pitch—a suggestion already put forward in a somewhat different form by Julius. In recent years theories of atomic structure have found favour in which the electrons are regarded as describing orbits, probably with great rapidity. If the electrons are sufficiently numerous, there may be an approach to steady motion. In case of disturbance, oscillations about this steady motion may ensue, and these oscillations are regarded as the origin of luminous waves of the same frequency. But in view of the discrete character of electrons such a motion can never be fully steady, and the system must tend to radiate even when undisturbed. In particular cases, such as some considered by Professor Thomson, the radiation in the undisturbed state may be very feeble. After disturbance, oscillations about the normal motion will ensue, but it does not follow that the frequencies of these oscilla-

tions will be manifested in the spectrum of the radiation. The spectrum may rather be due to the upsetting of the balance by which before disturbance radiation was prevented, and the frequencies will correspond (with modification) rather to the original distribution of electrons than to the oscillations. For example, if four equally spaced electrons revolve in a ring, the radiation is feeble, and its frequency is four times that of revolution. If the disposition of equal spacing be disturbed, there must be a tendency to recovery and to oscillations about this disposition. These oscillations may be extremely slow; but nevertheless frequencies will enter into the radiation once, twice, and thrice as great as that of revolution, and with intensities which may be much greater than the original radiation of fourfold frequency.

"An apparently formidable difficulty, emphasised by Jeans, stands in the way of all theories of this character. How can the atom have the definiteness which the spectroscope demands? It would seem that variations must exist in (say) hydrogen atoms which would be fatal to the sharpness of the observed radiation; and indeed the gradual change of an atom is directly contemplated in view of the phenomena of radio-activity. It seems an absolute necessity that the large majority of hydrogen atoms should be alike in a very high degree. Either the number undergoing change must be very small or else the changes must be sudden, so that at any time only a few deviate from one or more definite conditions.

"It is possible, however, that the conditions of stability or of exemption from radiation may after all really demand this definiteness, notwithstanding that in the comparatively simple cases treated by Thomson the angular velocity is open to variation. According to this view,

the frequencies observed in the spectrum may not be frequencies of disturbance or of oscillations in the ordinary sense at all, but rather form an essential part of the original constitution of the atom as determined by conditions of stability."

4. *Canal Rays.*—A fact of first-rate importance in connection with the theory of radiation has recently been observed by Johannes Stark (see *Physikalische Zeitschrift*, December 15, 1905). It is that canal rays (p. 119) show a displacement of the spectroscopic lines of the gas they traverse in accordance with their own velocity. They show, in fact, the "Doppler effect." Doppler's principle asserts that the wave-length of a wave is apparently increased if the source is moving away from the observer, but diminished if it is moving towards him. The ratio in which this is done is the same as the ratio of the speed of the source to the speed of light. This was exactly verified by Stark in hydrogen, and by Hermann in nitrogen. Canal rays have a speed of some 200 kilometres per second, whereas the speed of light is 300,000 kilometres per second. A difference of 1 in 1500 of the wave-length is easily observed in the spectroscope.

This new observation proves that radiation is not due to collision, or at least not maintained by it. For the first time we have under our eyes bodies whose state of motion can be confronted with their own radiation. The canal ray particles are positively charged nuclei of matter, the quickest among them being simply positive atoms, *i.e.* atoms rendered positive by losing one or two electrons. These, then, are capable of radiating spectrum lines with the aid of those more closely attached electrons whose existence has already been postulated. The detachable electrons do not generate spectrum lines. Their

revolutions are irregular and greatly disturbed. Another observation by Stark brings this out clearly. He finds that the bands in the spectrum exhibit no Doppler effect; that is to say, the mechanism generating these bands is stationary. This can only mean that it is unchanged, that it consists, in fact, of neutral gaseous atoms or molecules. When the detachable electrons radiate they do so in all sorts of periods, and their band spectrum overlays and obscures the lines of the more closely-linked electrons.

The existence of the latter, with their comparatively undisturbed orbits, furnishes a new support for the electron theory of magnetism.

5. *Metallic Conduction.*—An admirable summary of the electron theory of metallic conduction was given by Prof. J. J. Thomson in a lecture delivered before the London Institution of Electrical Engineers on February 21, 1907. If the electrons move free in the metal to any considerable extent, they must be in thermal equilibrium with its molecules. This means that the average kinetic energy of the electron must equal the average kinetic energy of, say, a hydrogen molecule having the same temperature. Its mass being much smaller, it must make compensation by its higher speed. The square of its velocity must be 3400 times the square of the velocity of the hydrogen molecule. At the temperature of freezing water it must be about 10^7 cm. per second. The darting about of these electrons produces no continuous current, since they dart about equally in all directions, unless an electro-motive force acts upon them. The additional velocity then acquired or lost by the electrons is as a rule much smaller (say, a hundred times) than their heat velocity. If t is the interval between two collisions, X the electric force,

and e and m the charge and mass of the electron, the acceleration is $\frac{Xe}{m}$, and the velocity acquired under this acceleration during each free excursion is $\frac{Xe}{m}t$. The average electric velocity is therefore $\frac{1}{2}\frac{Xe}{m}t$. Call this u. Then the amount of electricity that will pass through unit area in unit time will be $nue = \frac{1}{2}\frac{Xne^2}{m}t$, where n is the number of electrons per cubic cm. This is the current, and the E.M.F. being X, we get the conductivity by dividing the current by X, so getting $\frac{1}{2}\frac{ne^2}{m}t$. This is also the specific conductivity, since we are considering 1 c.c. Its dimensions are $L^{-3}\ M^{-1}\ E^2\ T$, or the same as those given on p. 297.

If λ is the free path of an electron, t may be put $= \frac{\lambda}{v}$, where v is the thermal velocity of an electron, which, as we have seen, is but slightly affected by the electric acceleration. Now the thermal conductivity of a gas, as determined in the kinetic theory of gases, is $\frac{1}{3}n\lambda v a$, where $a\theta$ is the kinetic energy of any molecule of any gas at a temperature θ. The value of a is about $1{\cdot}5 \times 10^{-16}$, and $\frac{1}{2}mv^2 = a\theta$.

The ratio of the thermal to the electrical conductivity is obtained by dividing the two expressions. It is $\frac{4a^2\theta}{3e^2}$. In this formula, both n and λ go out, and nothing remains that would be characteristic of the metal. Hence the ratio of the two conductivities should be the same in all metals at a given temperature (Law of Wiedemann and Franz).

This assumes, of course, that the thermal conductivity is due entirely to the electrons, and not to the atoms of the metal. If the latter also take part in thermal con-

duction the ratio varies, and we get thermo-electric effects.

The actual ratio as calculated by Thomson is $6{\cdot}1 \times 10^{10}$ in C.G.S. units. The values found by Jaeger and Diesselhorst are 6·7 for copper, 6·8 for silver, 7·09 for gold, 6·36 for aluminium, 8·02 for iron, and 11·0 for constantan ($\times 10^{10}$). The ratio being proportioned to the absolute temperature, its temperature coefficient should be 0·365 The actual value for copper is 0·39, silver 0·37, and gold 0·36.

There is an immense amount of energy radiated owing to the periodical stoppage of the electrons by collision. These stoppages, as we know, give rise to Röntgen rays, and many of these no doubt penetrate beyond the surface of the metal. This may account for the blackening of photographic films by such metals as zinc. But most of the radiation is reabsorbed by the metal, and only a small proportion is actually lost, to be recovered in the form of radiation from without. The energy actually transferred within 1 c.c. of the metal is, according to Thomson, equal to that turned out by an electric supply station of considerable dimensions.

A simple representation of the Peltier and Thomson effects is given by the same author in his "Corpuscular Theory of Matter," p. 97. It is worded as follows (substituting the word "electron" for "corpuscle"): "These effects on the theory first discussed, that electrons are distributed throughout the metal and are in temperature equilibrium with it, may be regarded as arising in the following way. If there are n electrons per unit volume, and v is their average velocity, then through unit area in the metal, $\frac{1}{6}nv$ electrons will in one second pass through in one direction. Hence if we have two metals, A and B,

in contact, and if nv in A is not the same as in B, the number of electrons that flow from A to B will not be the same as the number that flow from B to A. To fix our ideas, let us suppose that the flow through A is greater than that through B; A will lose more electrons than it will gain, and so will become positively, while B will be negatively, electrified. This distribution of electricity will tend to diminish the flow of electrons from A and increase that from B, and the charges of electricity will accumulate until they have made the two flows equal, when things will be in a steady state. This accumulation of positive electricity on A and of negative on B will form an 'electric double layer,' between the coatings of which there is a finite potential difference which is a measure of the Peltier effect at the junction of the metals. Similarly, if the flow $\frac{1}{6}nv$ depends upon the temperature of the metal, the transport of electrons through each section of an unequally heated conductor will vary, and the state of the conductor cannot be steady: the difference in the amount flowing through different sections will produce an accumulation of electricity along the conductor; this will produce an electric force which, by increasing the flow where it was small, and diminishing it where it was large, will make the flow uniform throughout the conductor. These forces represent the Thomson effect."

L. Bloch (*Comptes Rendus*, Nov. 4, 1907) makes some new computations of the number of electrons per c.c. and of the interval between two collisions. This interval is really much shorter than would result from the calculation on p. 89, since the electrons, being in thermal equilibrium with the atoms, move with prodigious velocities (of the order of 10^7 cm. per second) even without any

external electric force, and this speed is but little changed by the acceleration due to the ordinary electric forces at our disposal. The duration of the interval of freedom ranges, according to Bloch, from $1\cdot96 \times 10^{-15}$ sec. in the case of silver and $1\cdot92 \times 10^{-15}$ sec. in the case of copper, through aluminium, zinc, sodium, and antimony, down to bismuth, in which it is only $0\cdot85 \times 10^{-15}$ sec. But the calculation of the time required for an average electron to get through the copper (p. 89) is unaffected by this thermal speed, which works both ways and cancels itself. The number of "compartments" or stoppages per cm. required to produce the actual resistance of copper is 14,000 instead of 50 millions, meaning that a freely flying electron penetrates on the average 0·000071 cm. of copper before it is stopped. (Lenard succeeded in making electrons pass freely through 0·00026 cm. of aluminium.) The calculation of the current supposes that each electron, after stoppage, commences its new fall *at once.* This, of course, is not the case. It passes 5000 times the interval of its free fall attached to some copper atom. But 5000 other electrons take its place meanwhile, so that the requisite number of electrons are always free. The total detachable electrons are estimated by Bloch (from optical data) at 2·6 quadrillion per c.c., or 21 to each atom. Silver has 33 electrons detachable from each atom, zinc 5·6, and bismuth only 1·2.

The formula which connects the conductivity with the absorption of light is $n^2 b = \sigma T$, where n is the refractive index, b the coefficient of absorption, σ the electrostatically measured conductivity, and T the period of the incident light. This formula shows that the absorption increases directly as the conductivity, and also (for slow waves) with the period. For rapid waves of short wave-length, $n^2 b$

becomes $<\sigma T$. But a simple calculation will explain why even the best conductors among electrolytes do not absorb light to any great extent. The conductivity of mercury is 10^{16}, whereas that of the best conducting solution of sulphuric acid is 7×10^{11}. For light waves of period 2×10^{-15}, we have therefore $\sigma T = 0{\cdot}0014$, and the coefficient of absorption 0·0008. In mercury, $\sigma T = 20$, and since the refractive index for yellow light is 1·87, b becomes 5·7. In the former case the light only loses 0·5 per cent. of its intensity by traversing its own wave-length, and 2·15 per cent. by traversing 1 cm. In the case of mercury, the light is weakened in the large proportion of $10^{16} : 1$ by traversing its own wave-length.

Jean Becquerel has lately (see *Comptes Rendus*, Nov. 11, 1907) discovered an effect of temperature on the absorption bands of crystals such as tysonite. These become more numerous and sharp when the crystal is immersed in liquid air at the temperature of $-188°$ C. The discoverer calculates that there are some 10,000 electrons engaged in this absorption in every c.c. of the crystal at ordinary temperatures, and about double that number at the temperature of liquid air.

6. *Theory of Magnetism.*—This has lately been further developed by P. Weiss (see *Journal de Physique*, September 1907, p. 661). The difference between paramagnetism and ferromagnetism much resembles that between a gas and a liquid. In both cases the mutual action of the molecules is decisively effective in one phase, and not in the other. Magnetic saturation is never even approached in feebly magnetic bodies, and is never complete even in strongly ferromagnetic bodies. Langevin considered the mutual influence of the molecular magnets as a matter very difficult to deal with mathematically, but Weiss has

greatly simplified this influence by showing that it may be considered as due to an internal field which he calls the "molecular field," and which may be taken theoretically as uniform. This molecular field plays the same part in ferromagnetism as the "internal pressure" does in liquids. Like this, it is extremely high, about 80 million units at ordinary temperatures. It is proportional to $\frac{\theta}{T - \theta}$, where θ is the temperature at which ferromagnetism disappears, and T is the absolute temperature. The paramagnetic susceptibility is, according to Curie, inversely proportional to the absolute temperature. It may be put $= \frac{C}{T}$, where C is Curie's constant. The value of this constant is, according to Weiss, directly proportional to the atomic weight and to the number of atoms in the molecule, and may therefore be used to determine this number. By this means, Weiss proves that at a temperature of 1280° C. iron is transformed into what is called δ-iron, and in this transformation the molecule is changed from a diatomic to a triatomic one. The susceptibility (always very small above 760° C.) increases by 50 per cent. at the transformation point.

A fairly successful attempt at unravelling the phenomena of hysteresis is based upon the remarkable behaviour of pyrrhotine, a crystal which has one direction of easy magnetisation. However weak the magnetising field may be, the crystal is immediately magnetised to saturation On reversing the field, the magnetisation jumps suddenly and completely round as soon as the field reaches a certain critical strength. The crystal possesses three different susceptibilities along three axes at right angles to each other, and when these and the corresponding demagnetising fields are known, all the phases of magnetisation

may be calculated. Iron may be regarded as a conglomerate of cubic crystals facing different ways, with a demagnetising field of 120 units in one direction, and practically infinite in a direction normal to it.

The curious magnetic properties of Heusler's alloys of non-magnetic elements (aluminium 16 parts, manganese 24 parts, copper 60 parts) are probably due to a raising of the temperature of transformation of manganese. Alloys often have widely different fusing points, &c., from their constituents. The neutral molecules may facilitate the orientation of the elementary molecular currents.

7. *Electrolysis.*—The quantitative theory of electrolysis has been worked out mainly in the line of determining the hydration of the ions, which (see p. 103) is chiefly responsible for the differences in their mobilities. Bousfield found that the potassium and chlorine ions are each combined with about five molecules of water, and the slower lithium ion with about twenty molecules. Buchböck (*Zeitschr. Phys. Chem.*, June 8, 1906) attacked the question by tracing the displacement of a non-electrolytic solute during the electrolysis of a conducting solution. He found that the chlorine ion is combined with three or four molecules of water, according to the concentration. The mobilities of the various ions have been redetermined by K. Drucker (*Zeitschr. Elektrochemie*, March 8, 1907), and found to be from 2 to 5 per cent. smaller than the values given on p. 104. (See also "The Application of the Electron Theory to Electrolysis," by E. E. Fournier d'Albe, *Transactions of the Faraday Society*, vol. iii., Part I.)

8. *Electrons and the Ether.*—Various attempts have been made to clear up the relations between electrons and the ether, notably by Thomson, Kelvin, Einstein, Schott, and

Lodge, but no comprehensive theory has been hitherto arrived at. No further evidence has been adduced in favour of the probability of the existence of positive electrons beyond J. Becquerel's observations of the absorption in tysonite. The anomalies of the Hall effect are explained by Thomson by considerations of the behaviour of electric doublets in a metal exposed to a magnetic field (see his "Corpuscular Theory of Matter").

As regards the shape of the electron, the evidence to date points to rigid spheres, unaffected by motion through the æther (Abraham).

9. *Magnetic Rays.*—A new species of rays has been discovered and studied by Augusto Righi (see *Rendiconti della R. Accademia dei Lincei*, February 2, 1908, and December 20, 1908. Reprinted and amplified in *La Materia Radiante e i Raggi Magnetici*. Zanichelli: Bologna, 1909). The rays are a species of cathode rays which, instead of being bent into circular paths by a magnetic field, follow the lines of force of the latter. The field must be a very strong one. According to the theory formulated by Righi, these rays consist of systems of positive atoms attended by revolving electrons. The magnetic field has the effect of increasing the stability of those combinations which happen to be moving along the lines of magnetic force, and whose electronic orbits are in accordance with the field itself.

10. *Metallic Conduction.*—In the course of a review on the modern views of the metallic state (*Zeitschrift für Elektrochemie*, July 15, 1909), E. Riecke makes some new determinations of the mean free path of free electrons, their number per metallic atom, and the diameter of the latter. He assumes that at the melting point the metallic atoms (considered as spheres) are in immediate

contact. This gives $1 \cdot 6 \times 10^{-8}$ cm. for the diameter of the copper atom, which agrees well with the value assumed on p. 83. The number of free paths of the electron per cm. is $0 \cdot 13 \times 10^{8}$ (instead of $0 \cdot 5 \times 10^{8}$ as assumed on p. 89). The number p of free electrons per atom may be calculated (*a*) from thermo-electricity; (*b*) from atomic heat; (*c*) from the refraction and absorption of light in metals. The values for p found by the three methods independently range (*a*) from 0·53 Bi to 1·22 Fe; (*b*) from 0·93 Al to 1·24 Sn; (*c*) from 2·04 Ni to 6·57 Al. The general average is 1·8 mobile electrons per metallic atom.

11. *Elements and Electrons.*—In his Presidential Addresses to the Chemical Society for 1908 and 1909, Sir William Ramsay has developed a new view of the chemical elements, according to which they are built up of positive nuclei together with groups of definite numbers (usually 8 or 16) of electrons. The addition or subtraction of the latter causes their atomic weights to deviate from perfectly regular series. It also brings about a total change in their chemical properties (see *Journal of the Chemical Society*, April 1909).

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